Improving lake-effect snowfall forecasts via UFS-based atmosphere-lake models

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WWE Seminar, Feb/8/2024

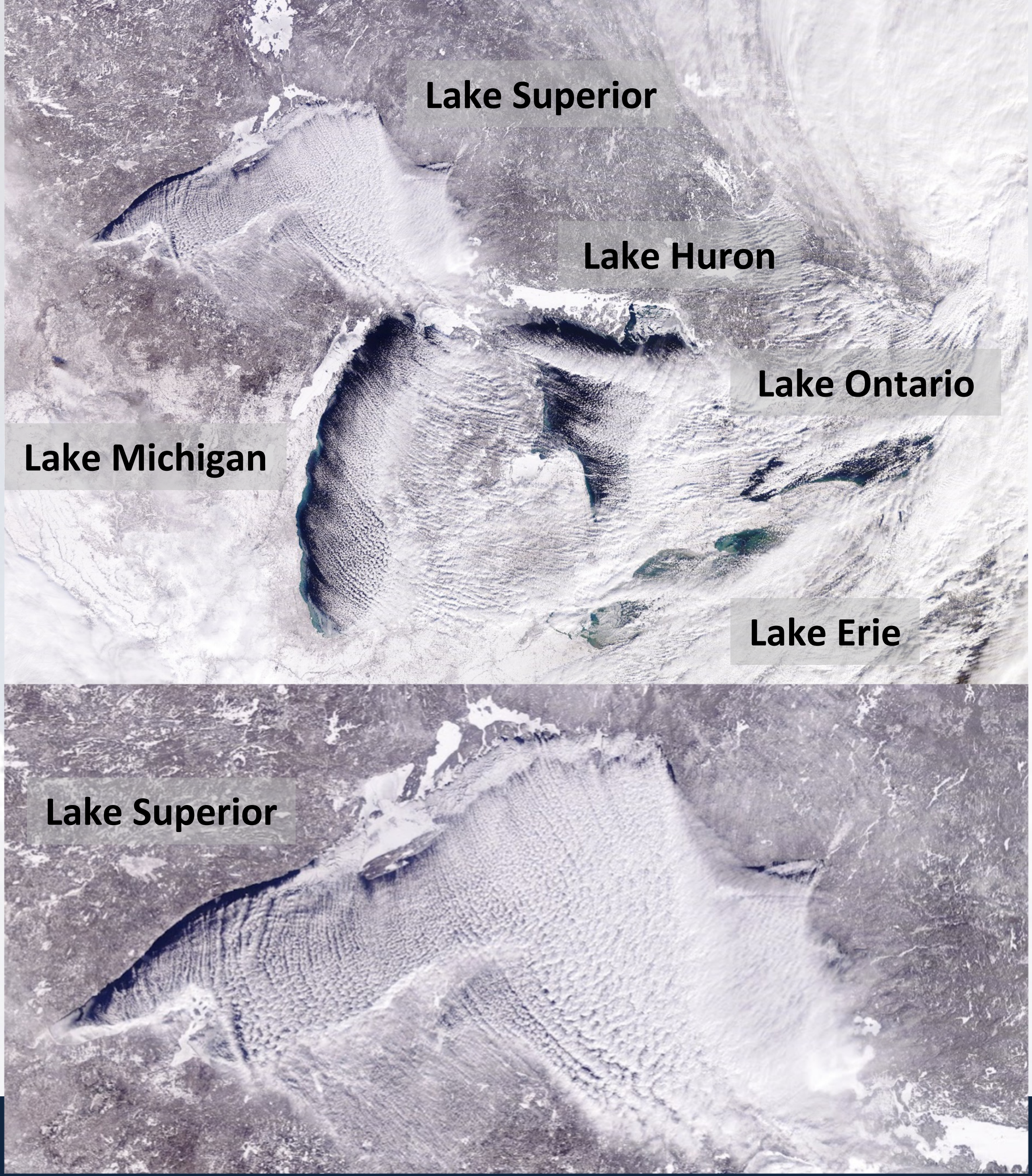
Cooperative Institute for Great Lakes Research
CIGLR
Great Lakes Science for Society

GLERL
Great Lakes Environmental Research Laboratory

Lake-Effect Snowfall

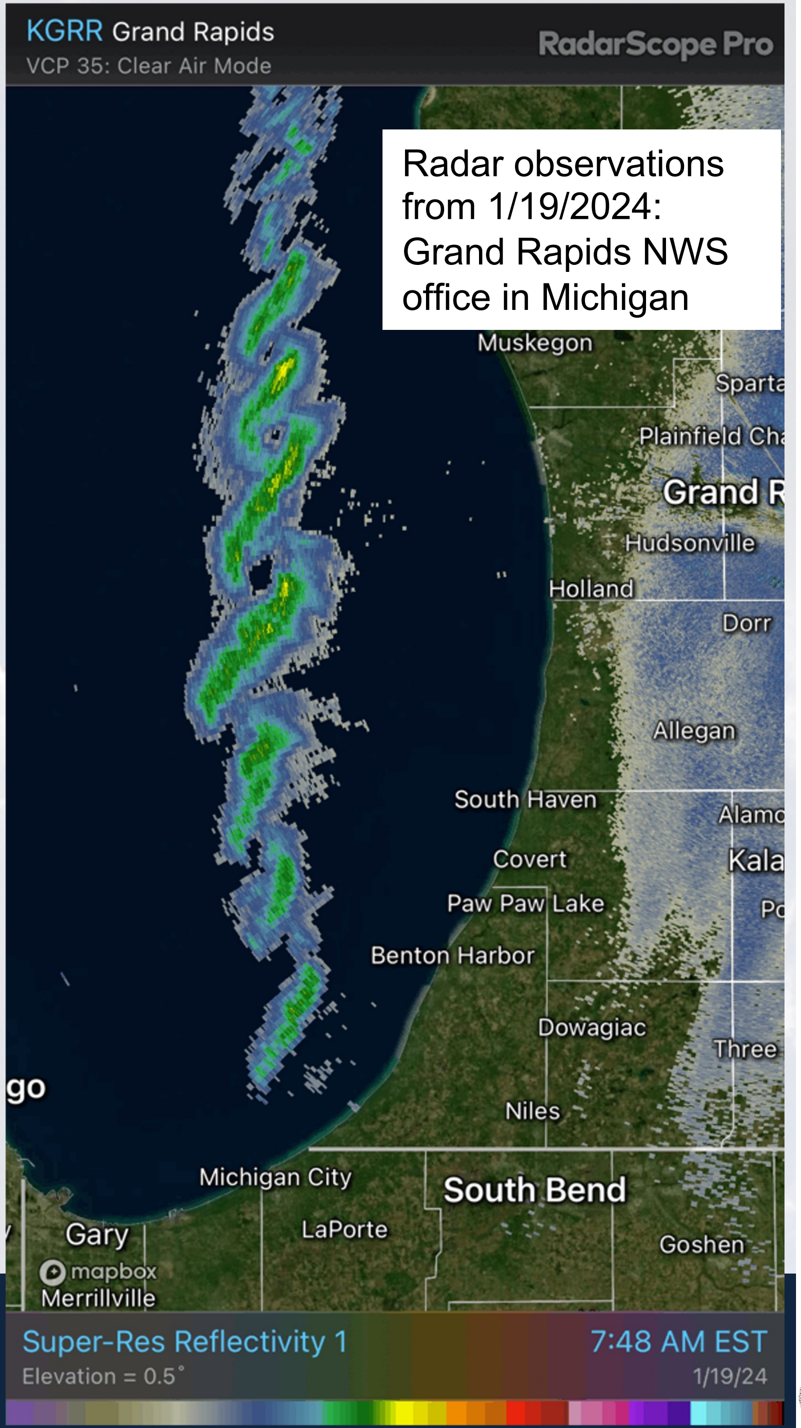
Lake-effect snowfall is challenging to accurately capture in NWP

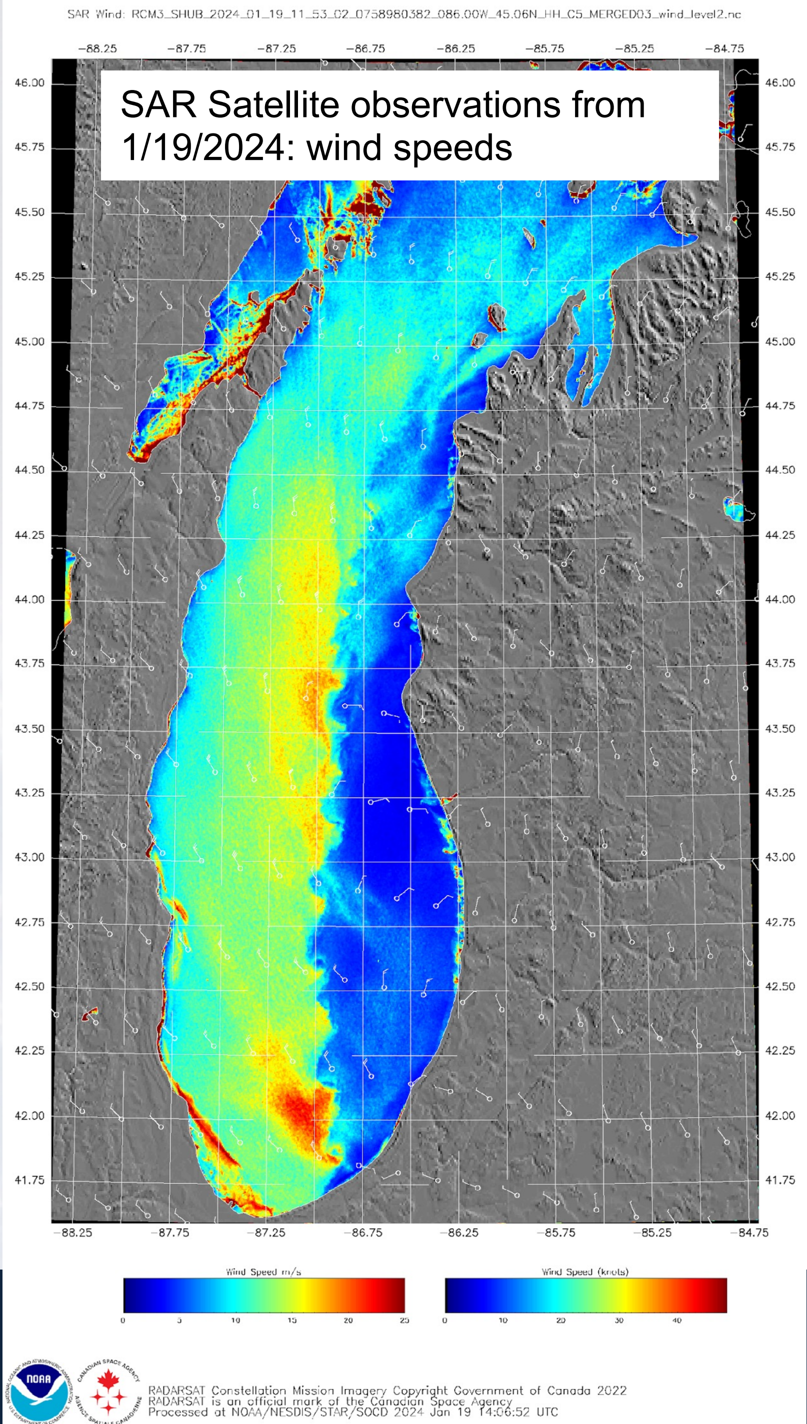
- Widths of lake-effect snowfall bands can be on the order of less than 5 km
- Extreme snowfall is possible along the downwind shorelines
- Sensitive to initial and lower boundary conditions like lake ice placement and lake surface temperatures (LST)



Lake-Effect Snowfall: Lake Michigan meso-vortices embedded in the Jan/19/2024 event

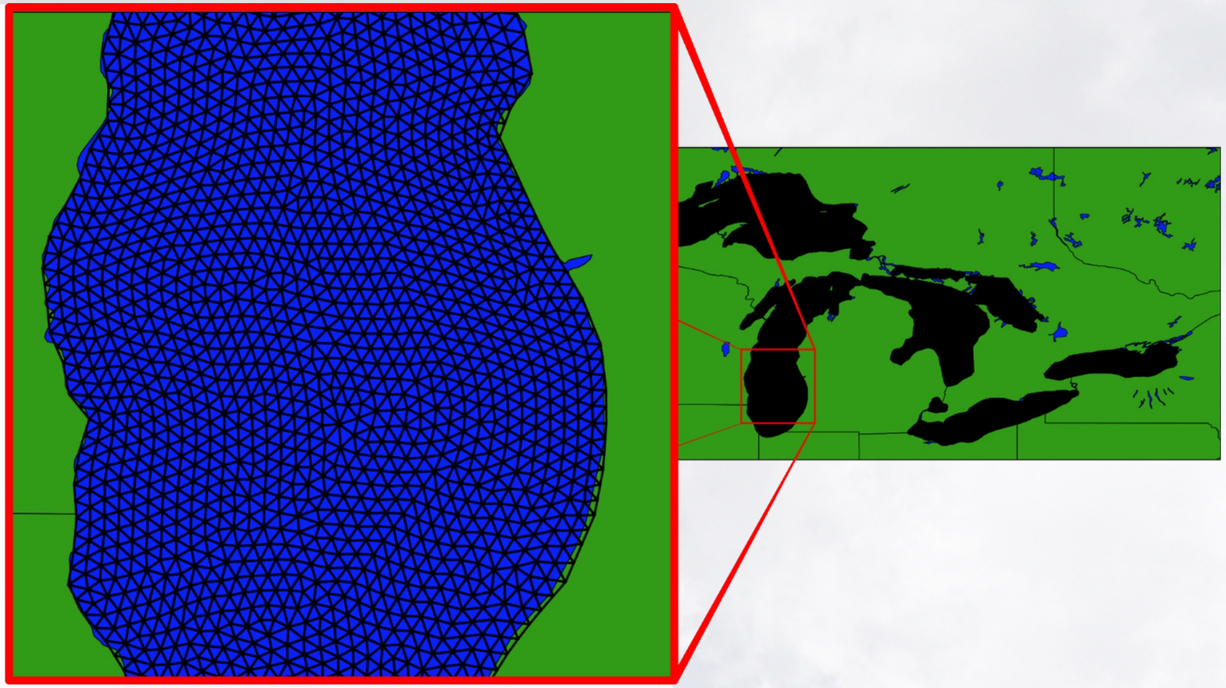
- Lake-effect snow events come in many forms (here with embedded meso-vortices)
- Can dump several feet of snow along the shorelines





Idea: FVCOM Model Provides Lake Conditions

- Use FVCOM coupled to the CICE ice model on an unstructured grid over the Great Lakes
- Couple FVCOM and NOAA's Unified Forecast System asynchronously (iteratively), models run separately
- **Replace satellite-based lake surface temperature (LST) and ice information in the NOAA UFS Short-Range Weather (SRW) / HRRR model with FVCOM's lake data:** LST, ice coverage, ice T from FVCOM

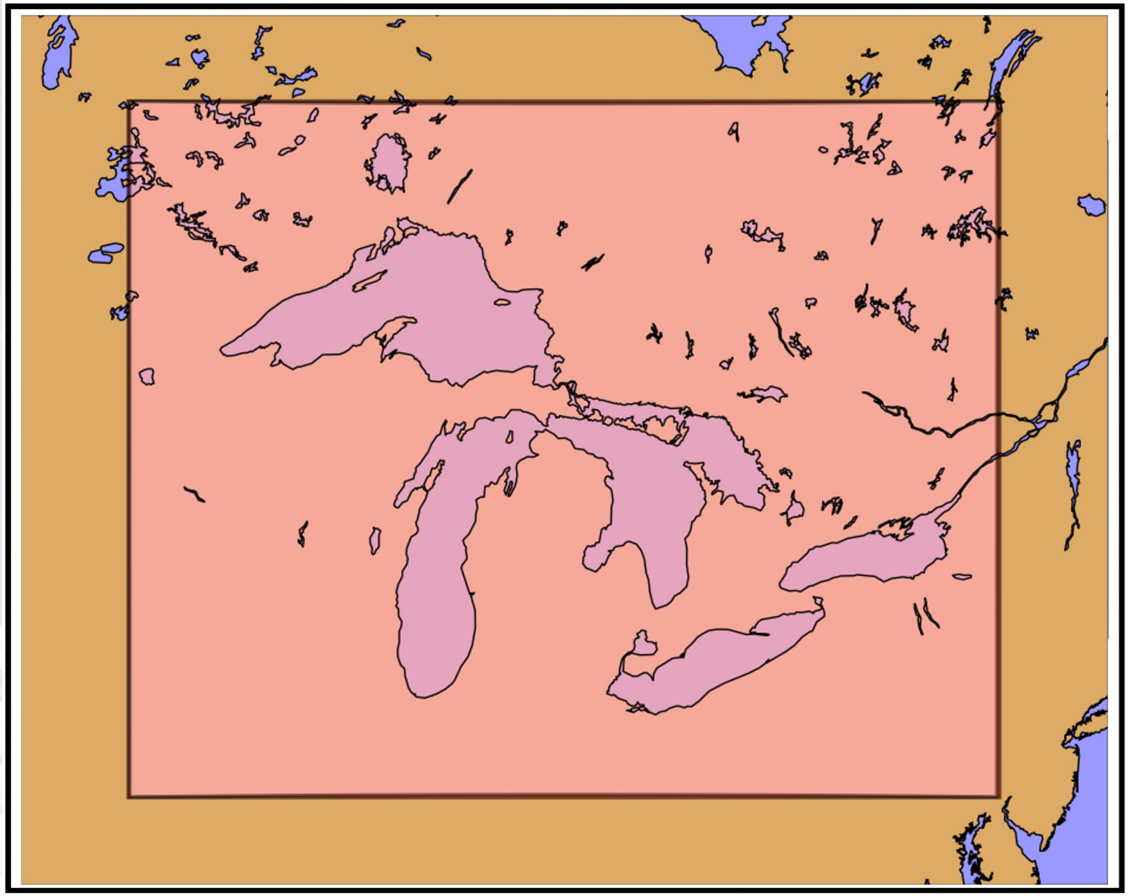


Finite-Volume Community Ocean Model (FVCOM): Base model for the operational Great Lakes Operational Forecasting System (GLOFS) at NOAA

FVCOM/HRRR coupling: Fujisaki-Manome et al. (2020)

Proof of Concept Studies: UFS-Short-Range Weather (SRW) Configuration for the Great Lakes (mimic RRFS)

- 3km horizontal grid spacing & 65 levels
- HRRR-like Physics Package as in RRFS
  - Using RUC Land Surface Model
- RAP Initial and Lateral Boundary Conditions
  - Lake surface boundary conditions can be updated hourly
- Same run time parameters as the parallel RRFS simulations NOAA conducts



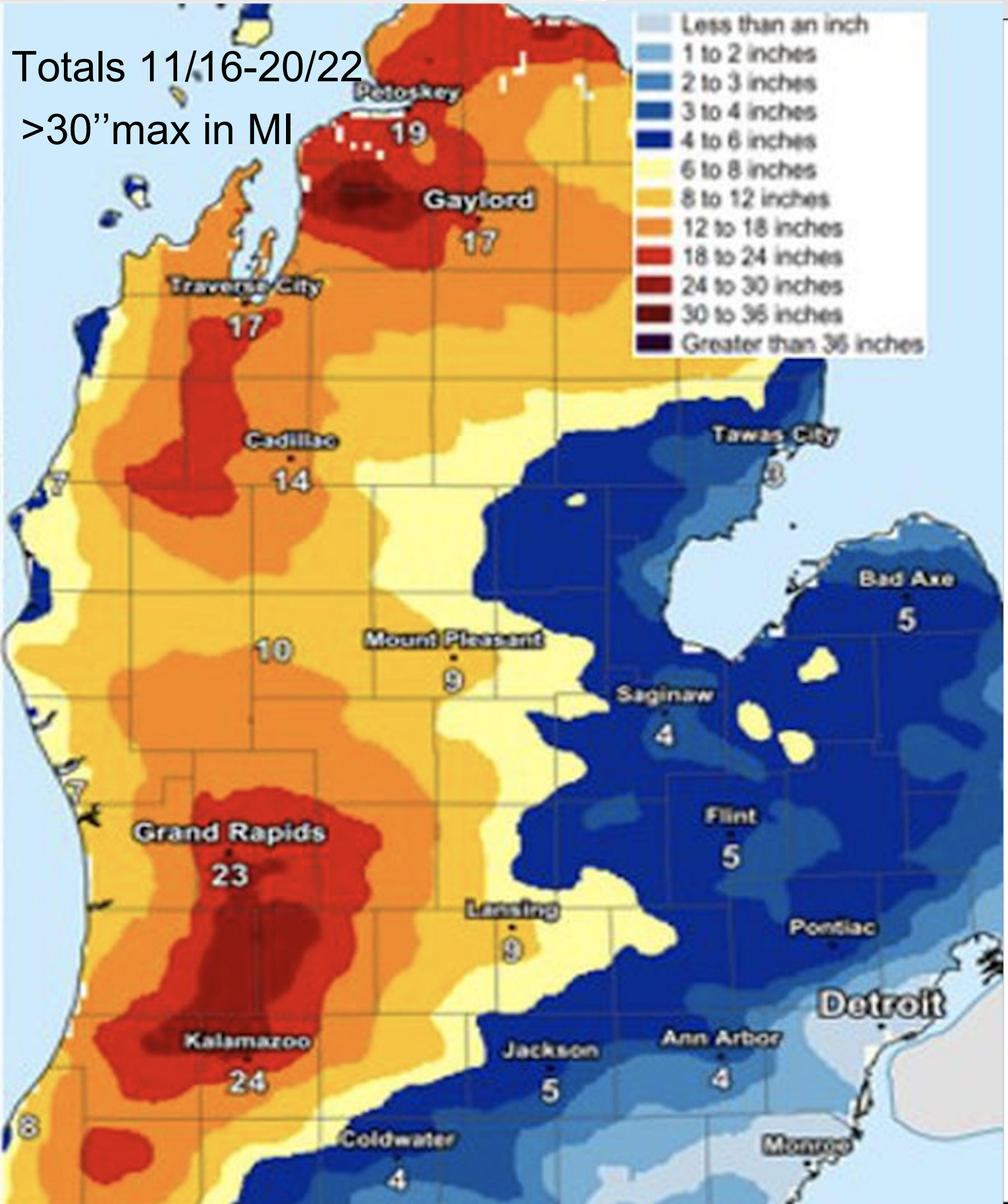
The NOAA RRFS Extended North American Domain too large for testing purposes:
Replace with **UFS Short-Range Weather (UFS-SRW)** Great Lakes Domain (red box)

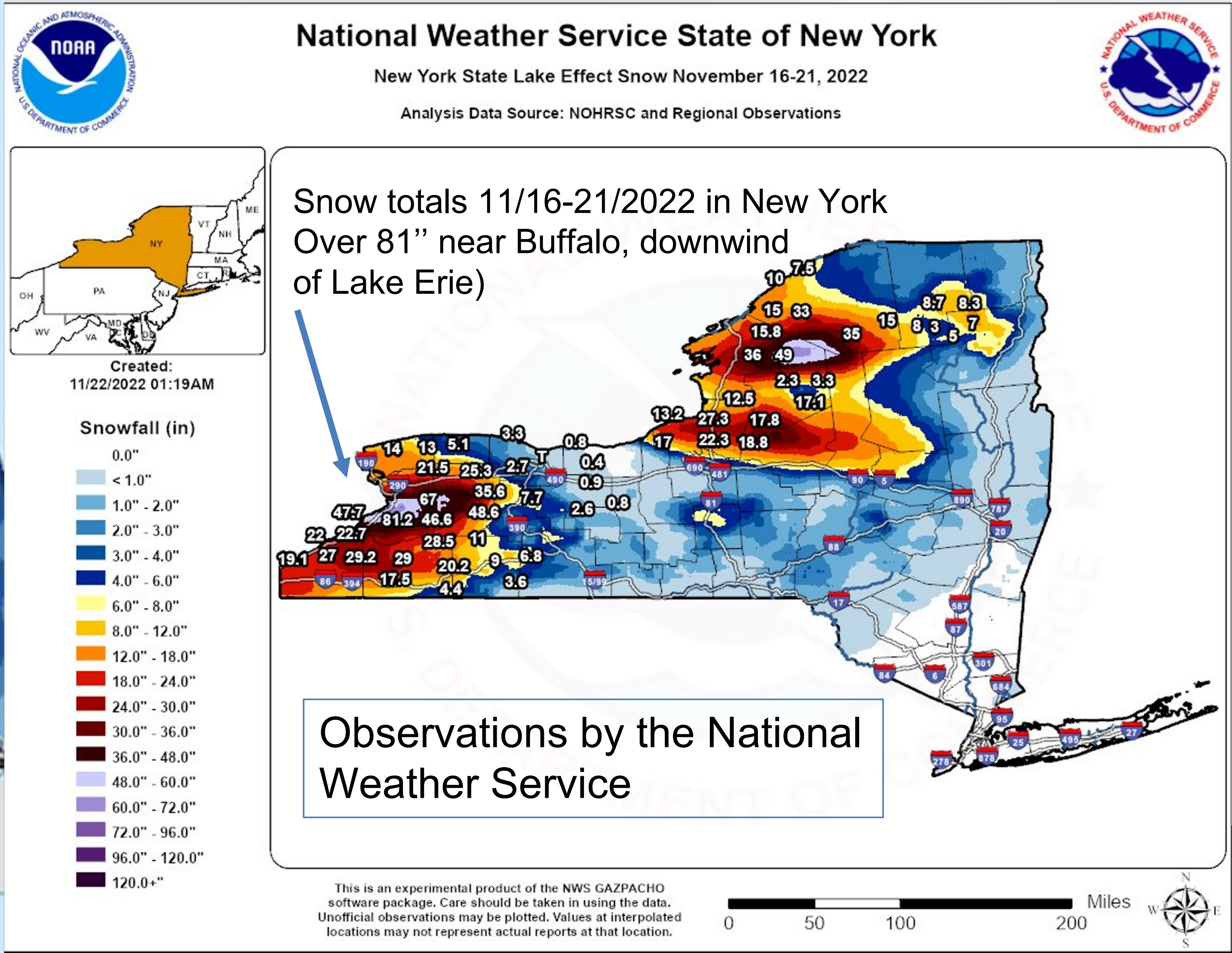
Lake Surface Configurations

- **<u>Control</u>**: Lake surface conditions (temperature and ice) are interpolated from the RAP initial conditions (GFS for RRFS-A) and do not change throughout the simulation
- **<u>Static</u>**: Lake surface conditions are initialized using FVCOM data and do not change throughout the simulation
- **<u>Dynamic</u>**: Lake surface conditions are initialized and updated hourly using FVCOM simulations

Pick a lake-effect snowfall case study from November/16-19/2022

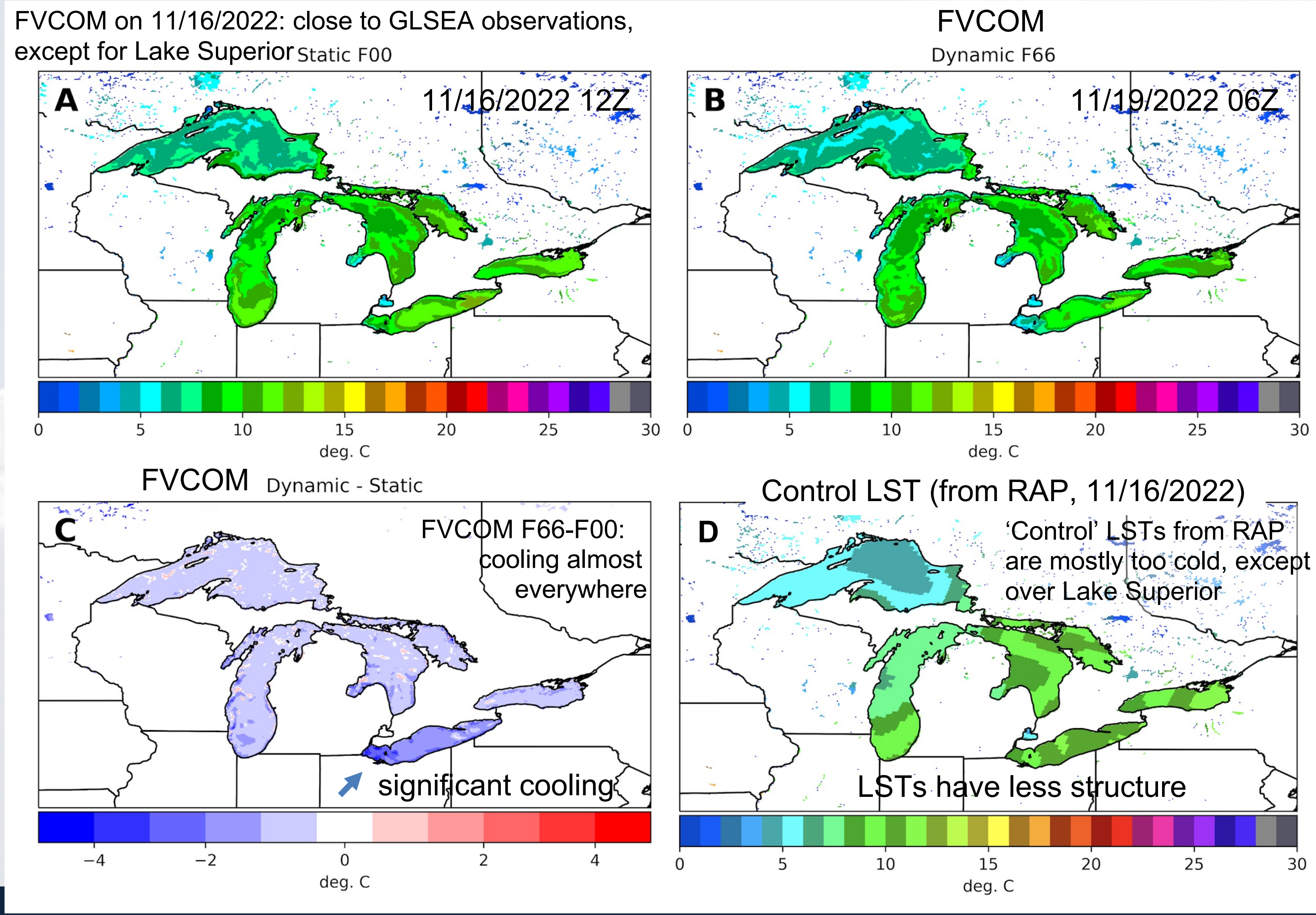
November 2022 Lake Effect Snowfall Event

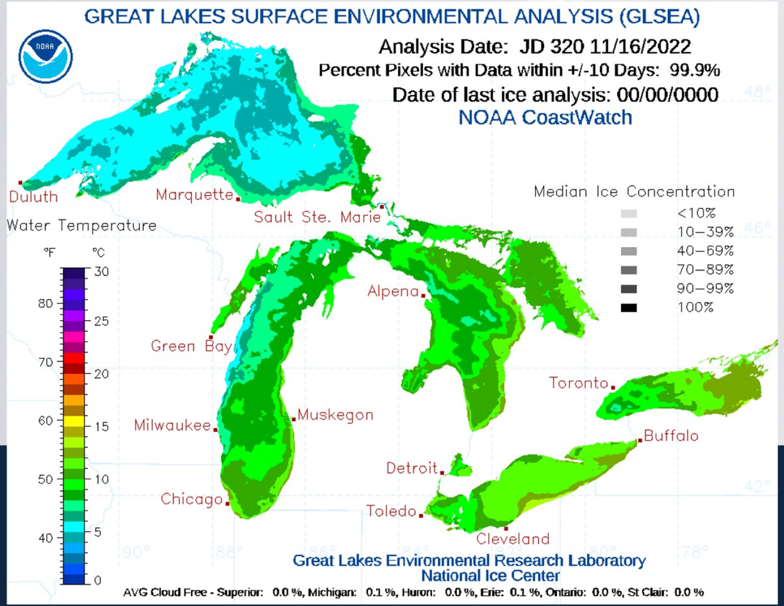




Nov. 2022 Lake temperatures: Static, Dynamic, Control

- Simulations start on 11/16/2022 12Z
- During the LES event the lake temperatures cool rapidly as shown in the dynamic FVCOM data after 66h hours, see B & C

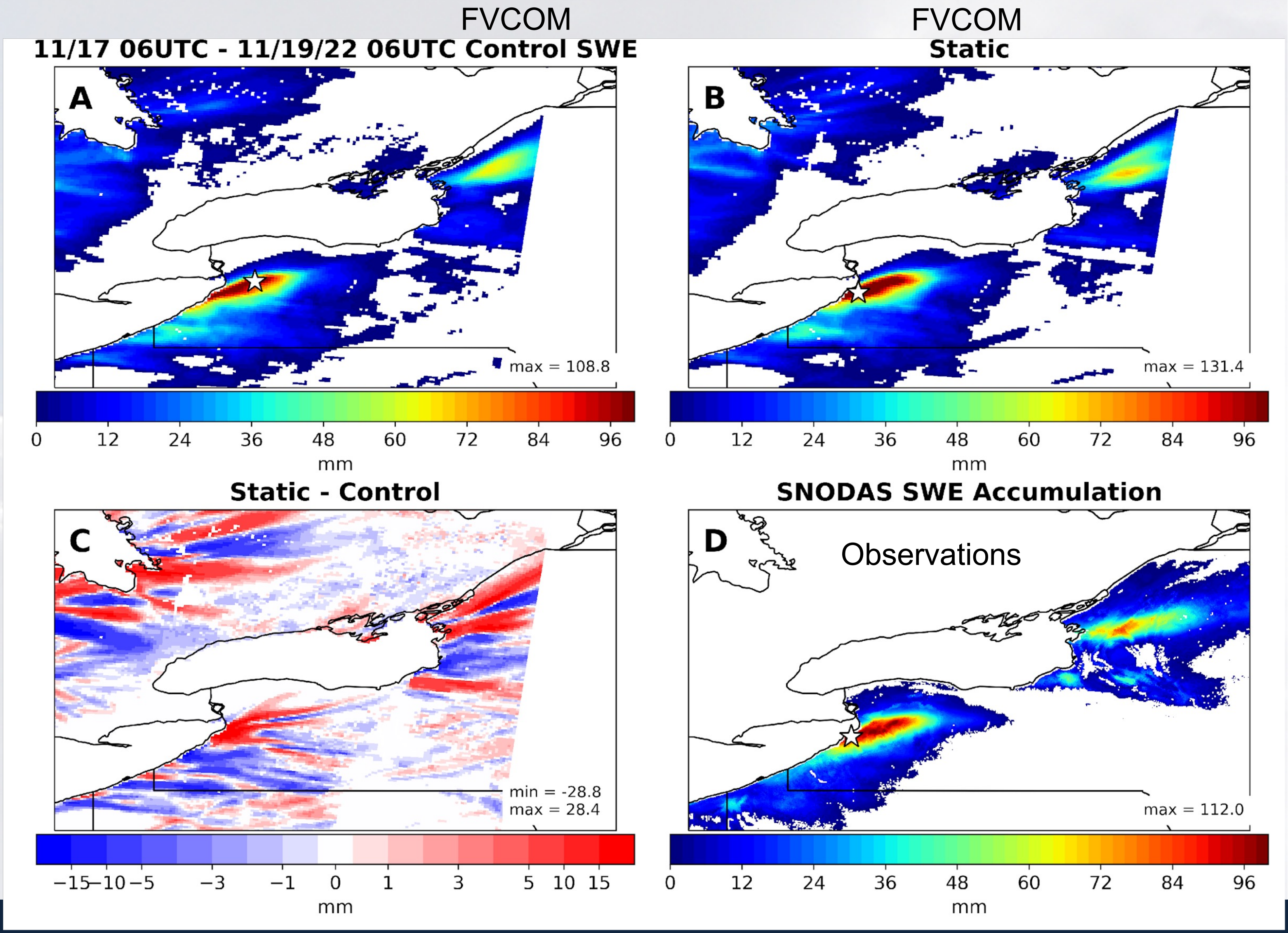




GLSEA: Lake temperature observations. NOAA CoastWatch

Forecast Performance: Snow Water Equivalent (SWE)

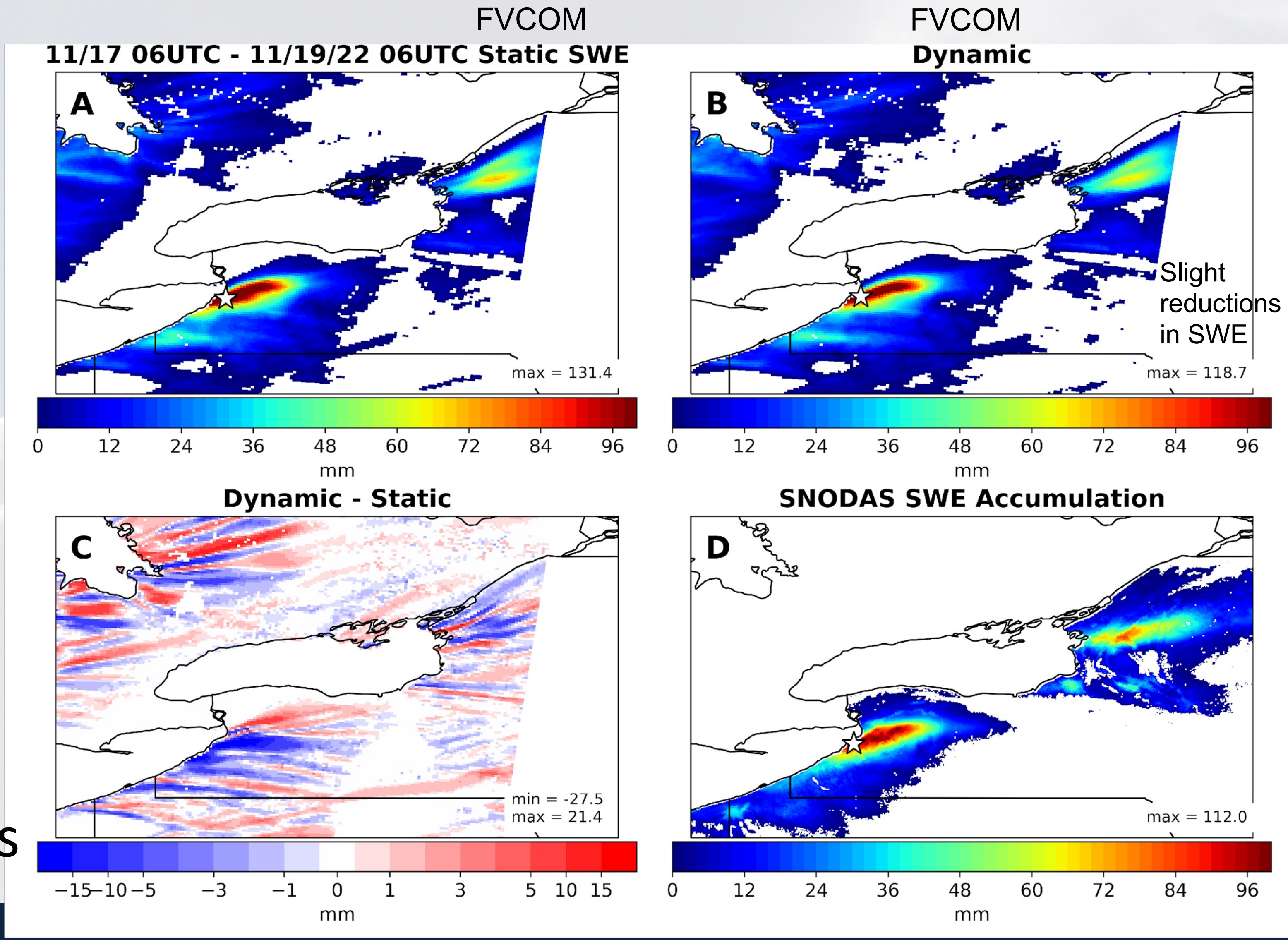
- UFS-SRW (Great Lakes) simulations start on 11/16/2022 12Z
- Evaluations of SWE over 48 hours compared to SNODAS observations (D)
- Simulation with ‘static’ lake conditions (B) from FVCOM slightly outperforms the ‘control’ (A) for Lake Erie and Ontario



Focus on Lake Erie and Lake Ontario

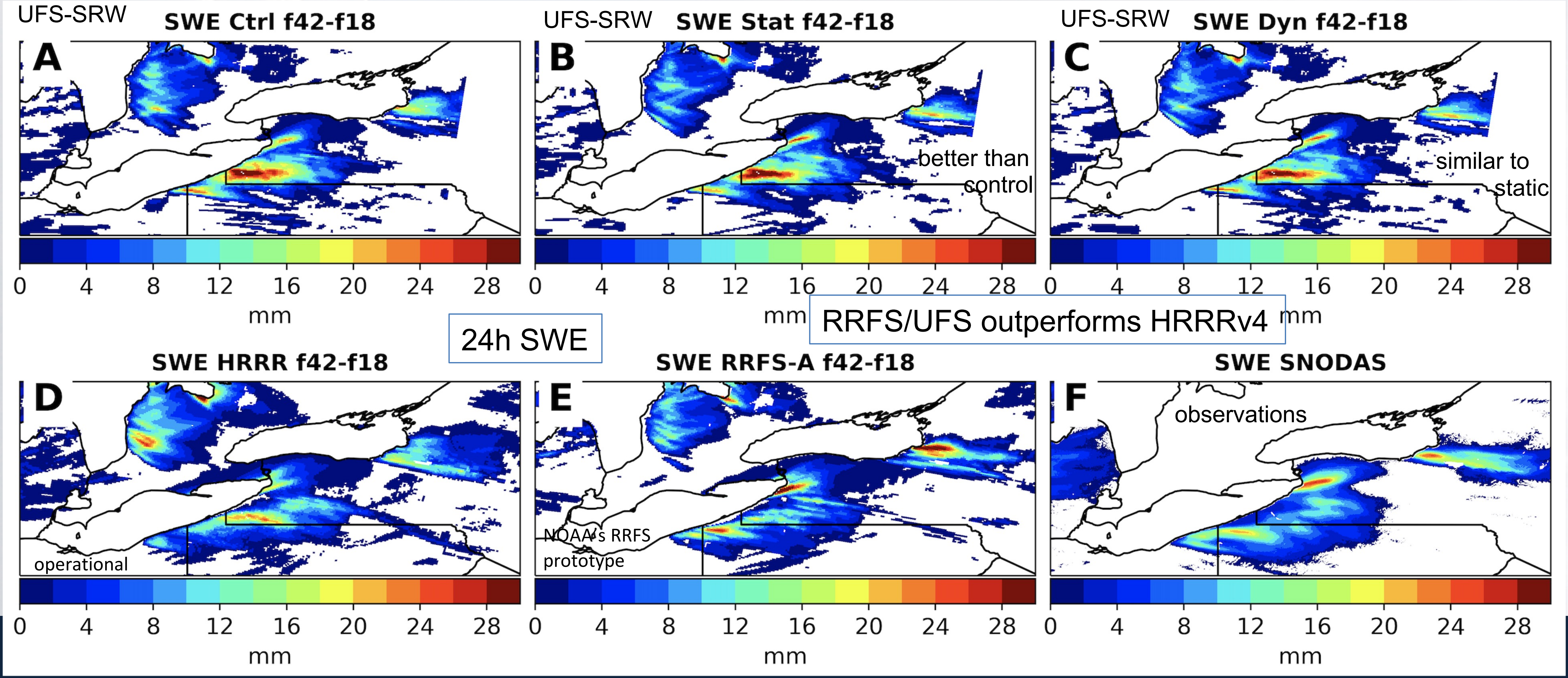
SWE Forecast Performance: Lake Erie & Ontario

- UFS-SRW (Great Lakes) simulations start on 11/16/2022 12Z, 2-day SWE
- Comparison: static versus dynamic FVCOM conditions
- Status today: Despite the considerable cooling of Lake Erie over the 2-day period, the dynamic (1hr) FVCOM lake updates in UFS-SRW produce similar SWE forecasts



Lake Erie/Ontario: UFS-SRW, HRRR, RRFS-A, SNODAS

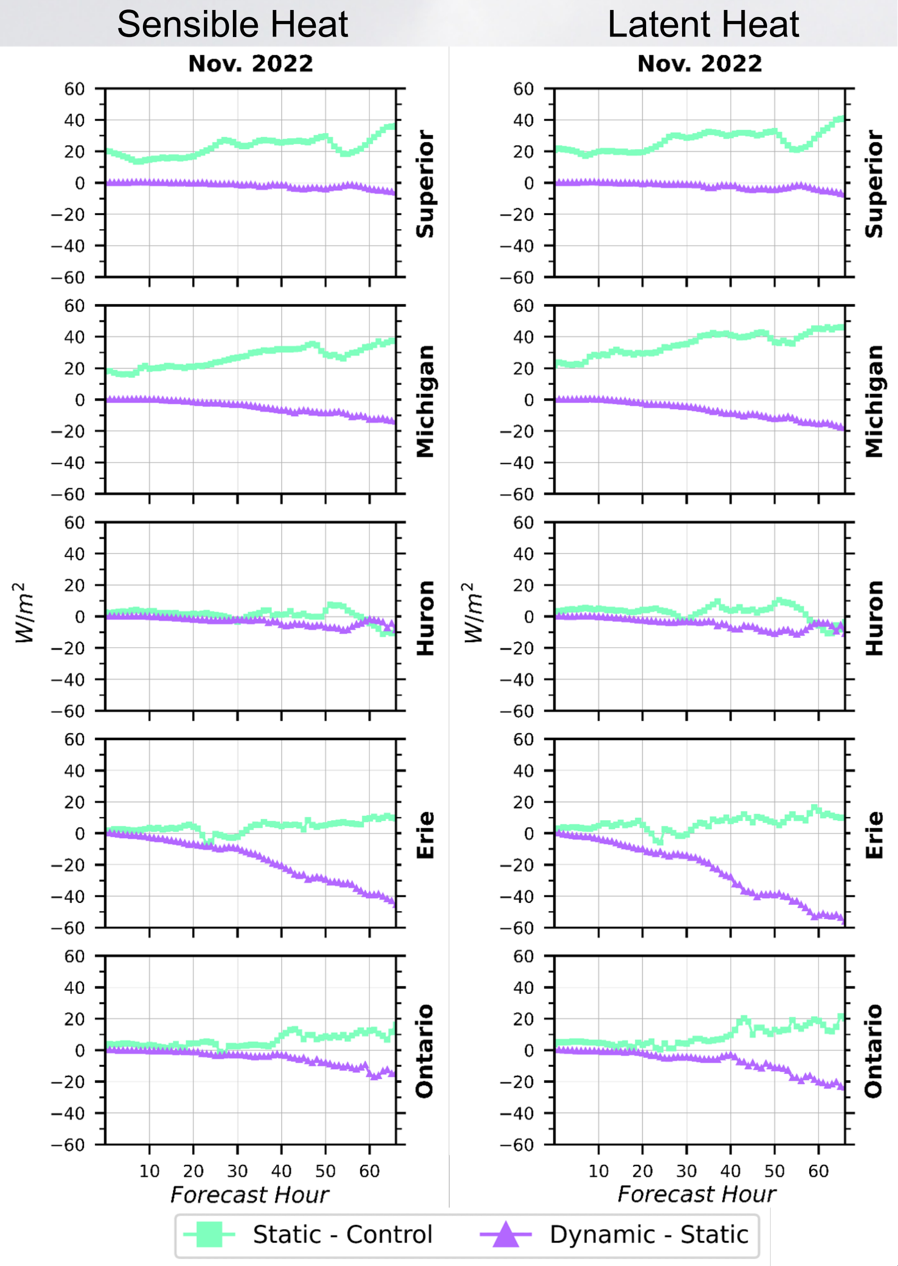
- RRFS/UFS forecasts improve with the FVCOM lake coupling along the Lake Erie and Ontario shorelines



Focus on Lake Erie & Lake Ontario

Lake-wide Averaged Heat Fluxes

- Graphs show the differences between Static-Control (green squares) and Dynamic-Static (purple triangles) in lake-wide averaged latent and sensible heat fluxes for each lake over the forecast period
- For the Static - Control, there are noticeable differences in sensible and latent heat fluxes over the entire forecast
- For the Dynamic - Static, these differences are minimal except for Lake Erie towards the latter half of the forecast
- *Anecdotally*, +/- 50 W m^{-2} is relatively accurate for heat fluxes for weather events (Bourassa et al. 2013)



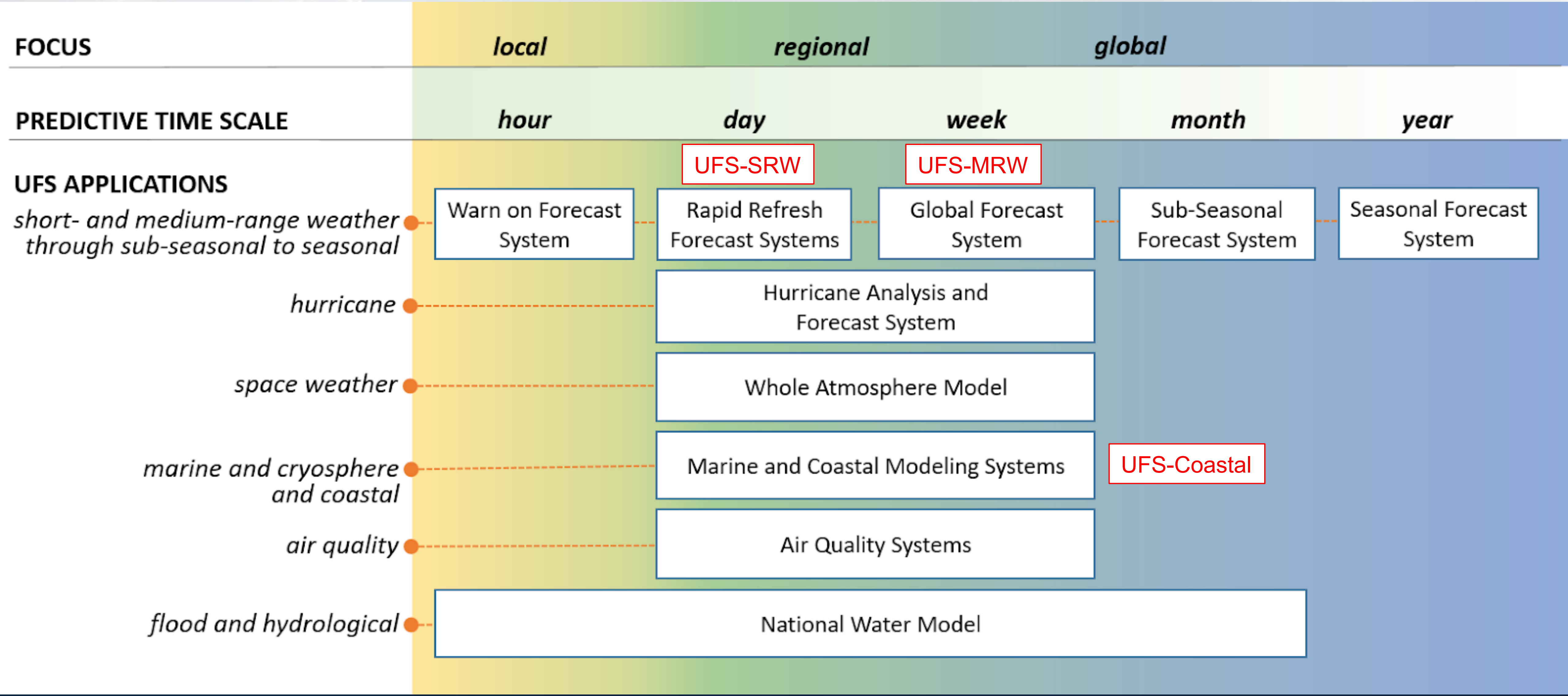
Current Status

- Inclusion of FVCOM lake conditions for temperatures and ice improves the forecasts of lake-effect events in comparison to using the ‘control’ satellite-derived boundary conditions in RRFS/UFS-SRW and HRRRv4
- Currently: Static and dynamic lake conditions produce similar snowfall amounts, this will likely change for 15-day simulations with UFS-MRW
- Successful Inclusion of static lake boundary data from the operational FVCOM-driven Great Lakes Operational Forecast System (GLOFS) into pre-operational RRFS-A on NOAA’s high-performance system WCCOS2, testing underway as part of the 2023-2024 Winter Weather Experiment
- To come: Replace the current ‘poor-man’s’ lake file coupling technique (overwrite the UFS lower boundary conditions file during the initialization) with the proper UFS coupling technique from the Earth System Model Framework (ESMF)

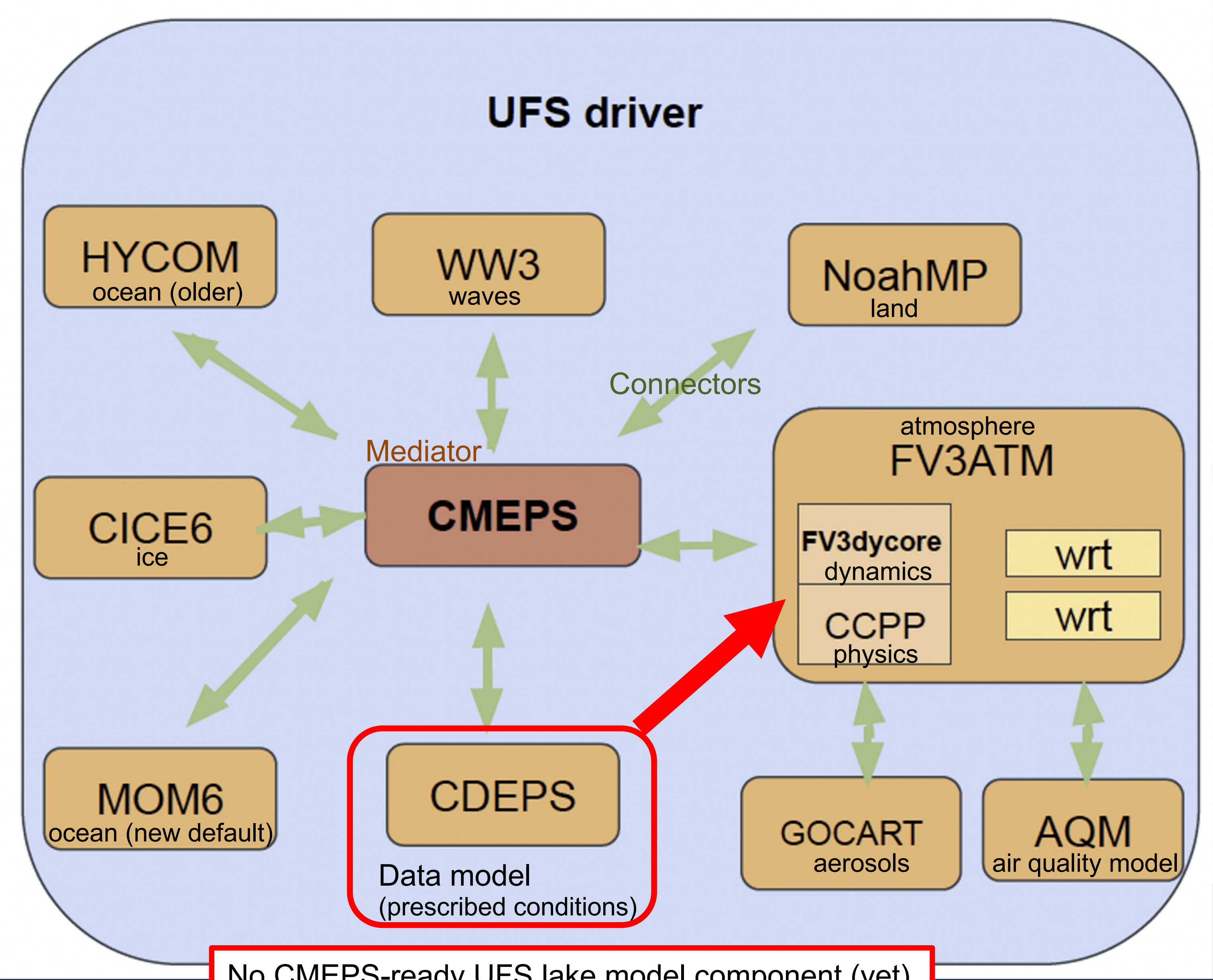
Overview of the Current Model Development Steps

- Coupling of the dynamic FVCOM lake conditions using the newest UFS ESMF-based coupling infrastructure: inlining the CDEPS data model
- ESMF enables the seamless inclusion of dynamic FVCOM lake conditions in both UFS-SRW/RRFS and the Medium-Range Weather (UFS-MRW) application
  - test the skill of a coupled UFS-MRW/GFS-FVCOM configuration
- 1-way coupling of FVCOM to the wave model WaveWatch III:
  - tests for Lake Erie and Superior are under way
- Upgrades & evaluation of the ice representation in FVCOME: CICE3 versus CICE6
  - Standalone CICE6 assessments are under way driven by FVCOM

Components of the Unified Forecast System (UFS)



Overview of the UFS with Current ESMF Infrastructure

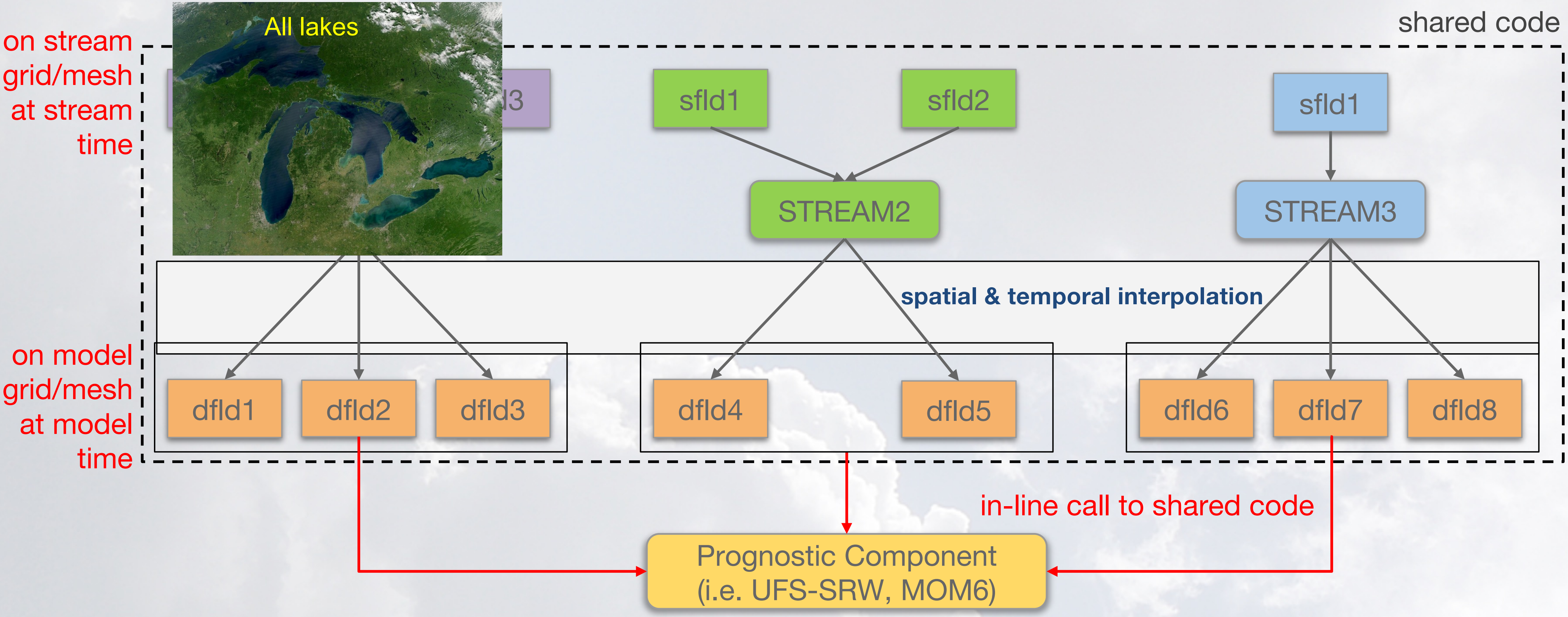


No CMEPS-ready UFS lake model component (yet)

- ESMF is the coupling infrastructure for the UFS
- Contains the ESMF elements:
  - UFS driver
  - CMEPS mediator:
    - requires NUOPC standard
    - central coupling unit
    - interpolations, averaging, flux calculations
  - Connectors:
    - performs interpolations
  - CDEPS data model:
    - for inactive model components, prescribe data

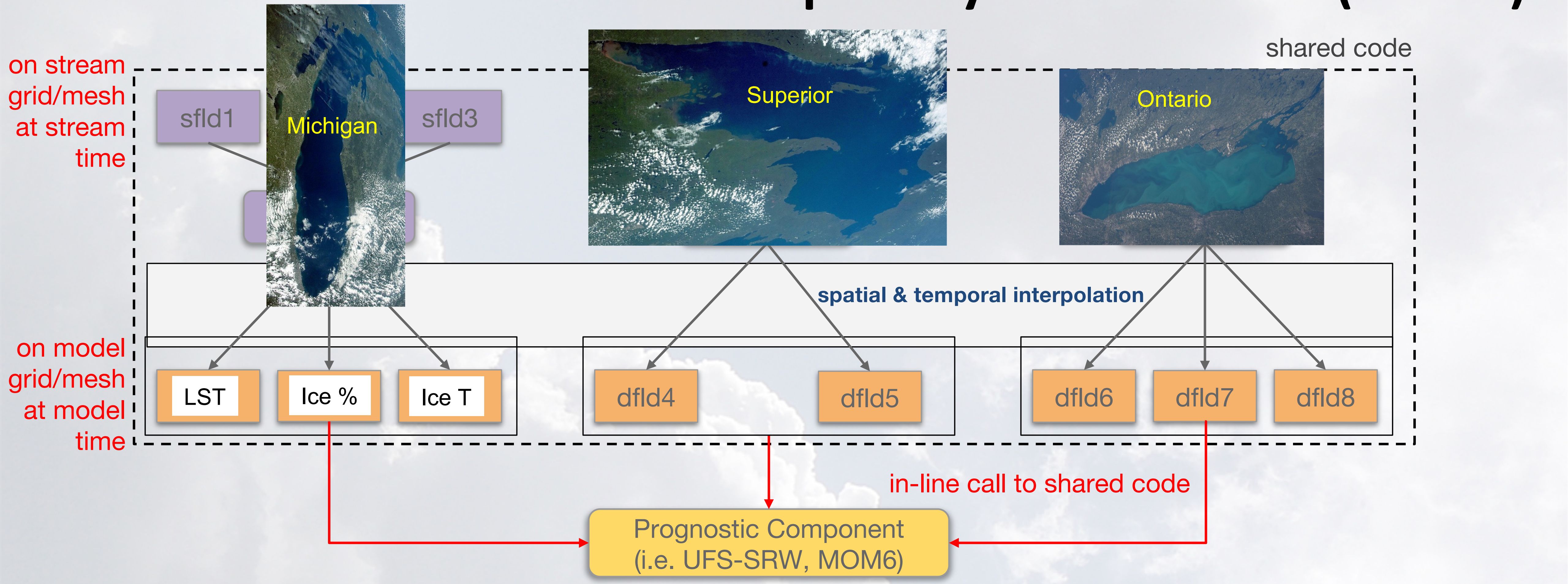
Idea: Introduce a CDEPS shortcut

To Come: Use an ESMF Inline Capability for Data Files (CDEPS)



- The Community Data Models for Earth Predictive Systems (CDEPS) contains a set of NUOPC-compliant data components along with ESMF-based share code that enables new capabilities in selectively removing feedbacks in coupled model systems.
- It can be used as a ESMF/NUOPC complaint component or as a inline call from the host model.

To Come: Use an ESMF Inline Capability for Data Files (CDEPS)



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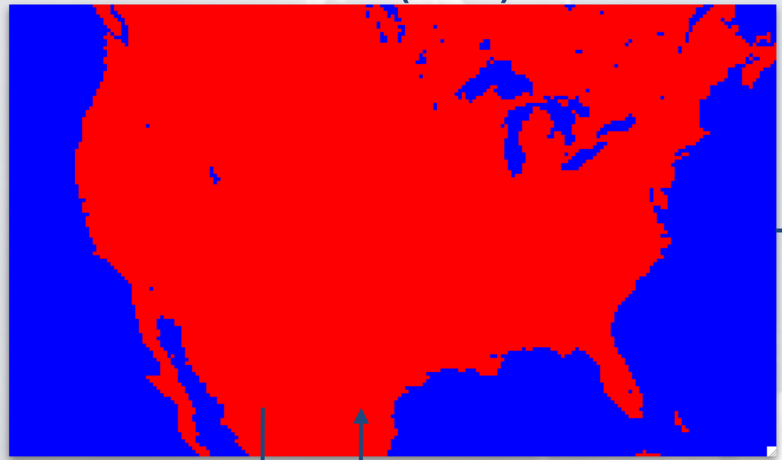
- It can be used as a ESMF/NUOPC complaint component or as a inline call from the host model.

To Come: Integrate CDEPS Calls into the UFS

UFS-SRW (RRFS) or UFS Medium-Range Weather (GFS) domain, here CONUS

RRFS CONUS Domain (25km)



Inputs:
dst mesh
time info

(1)

CDEPS inline calls

(2)

ESMF configuration file

stream.config

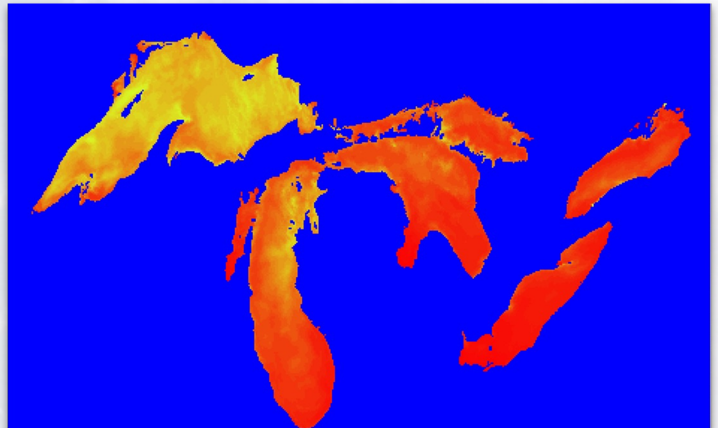
```
stream_info:                 stream01

taxmode01:                   limit
mapalgo01:                   consd
tInterpAlgo01:               linear
readMode01:                  single
dtlimit01:                   1.5
stream_offset01:             0
yearFirst01:                 2023
yearLast01:                  2023
yearAlign01:                 2023
stream_vectors01:            null
stream_mesh_file01:          INPUT_DATA/ESMFmesh.nc
stream_lev_dimname01:        null
stream_data_files01:         INPUT_DATA/tsfc_fv3grid_202318612_sub_fixed.nc
stream_data_variables01:     "twsfc So_t" "aice Si_ifrac" "vice Si_vice"
stream_dst_mask01:           1
```

(5)

CCPP Physics Layer: use LST & ice

(3) **spatial (conservative) and temporal interpolation**

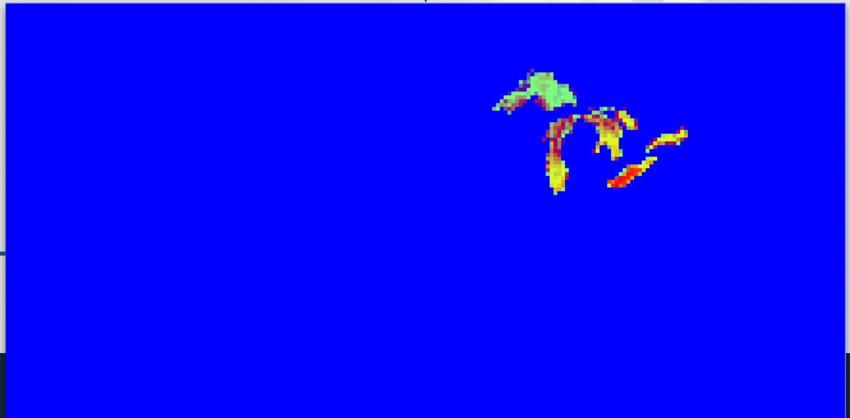


Input: FVCOM Output (LST and ice)

new scheme:
sfc_data.{F|meta}

LST and ice

(4)



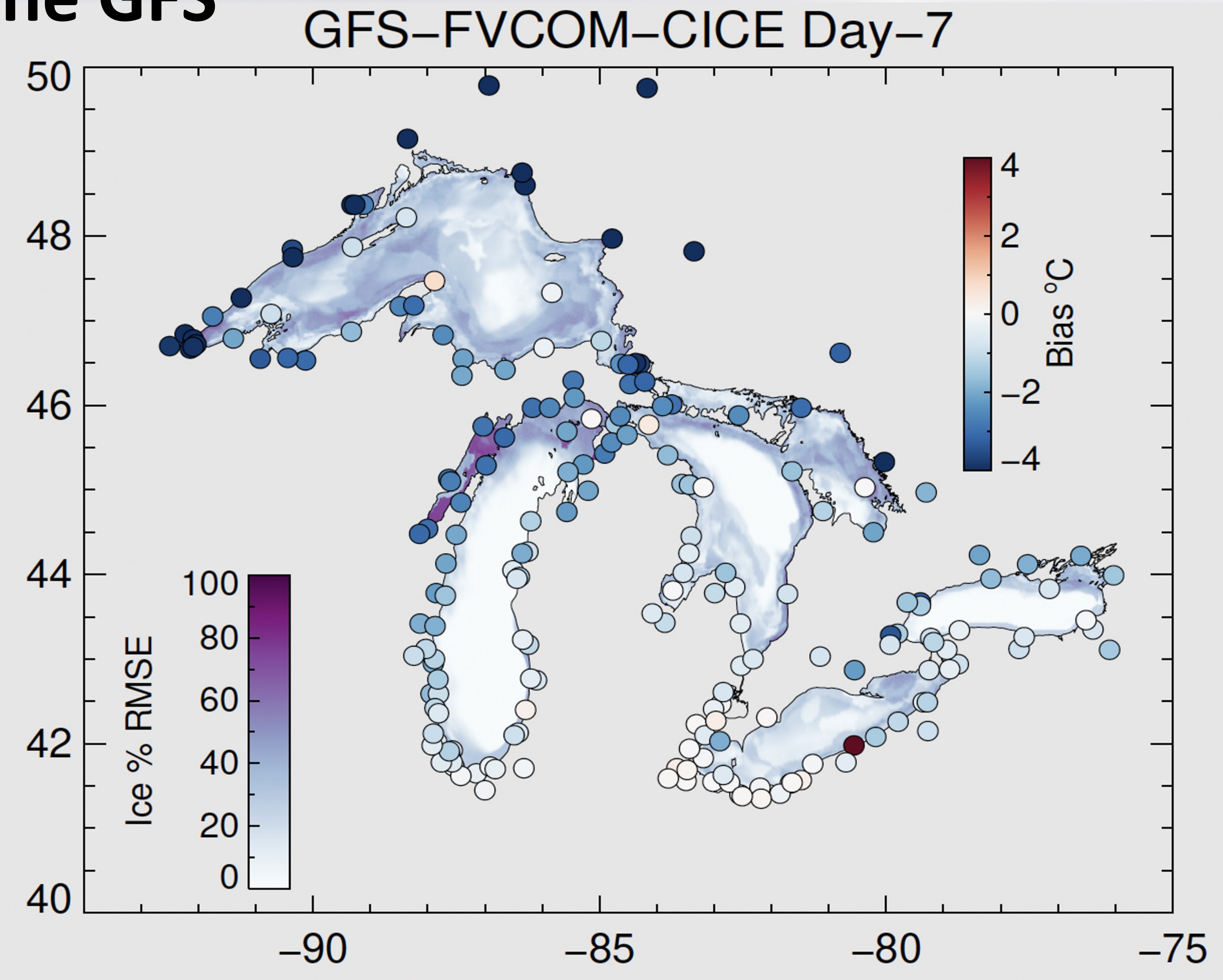
Output: FVCOM Output (LST/ice on RRFS grid)

https://github.com/uturuncoglu/ufs-weather-model/tree/feature/inline

*** Note that scales are not same in the plots**

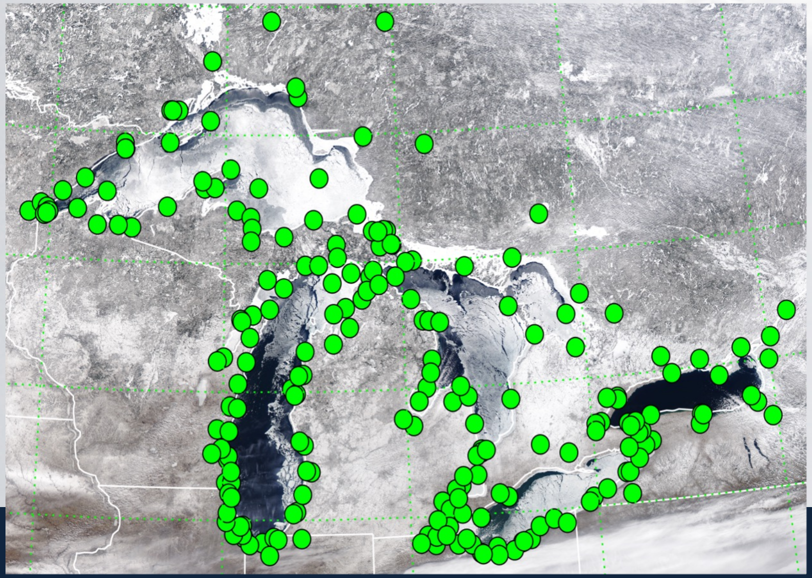
Test: FVCOM driven by the GFS

- Pick 8 16-day forecast periods from Jan-April 2022
- Drive FVCOM-CICE with ‘perfect’ initial lake temperatures and ice (use ice observation from the US National Ice Center, NIC) with 3hr/6hr UFS-MRW (GFS) weather forecasts for 16 days
- Compare the GFS temperature forecasts at day 7 with 161 station observations along the Great Lakes shorelines (ensemble means denoted by circles colored with T bias)
- Evaluate the lake ice (%) RMSE and bias at day 7 as a response to the (mostly cold) T bias from the GFS, GFS also has low-wind and high cloud cover biases
- Leads to over-icing, especially in the north (Superior) and over Lake Erie

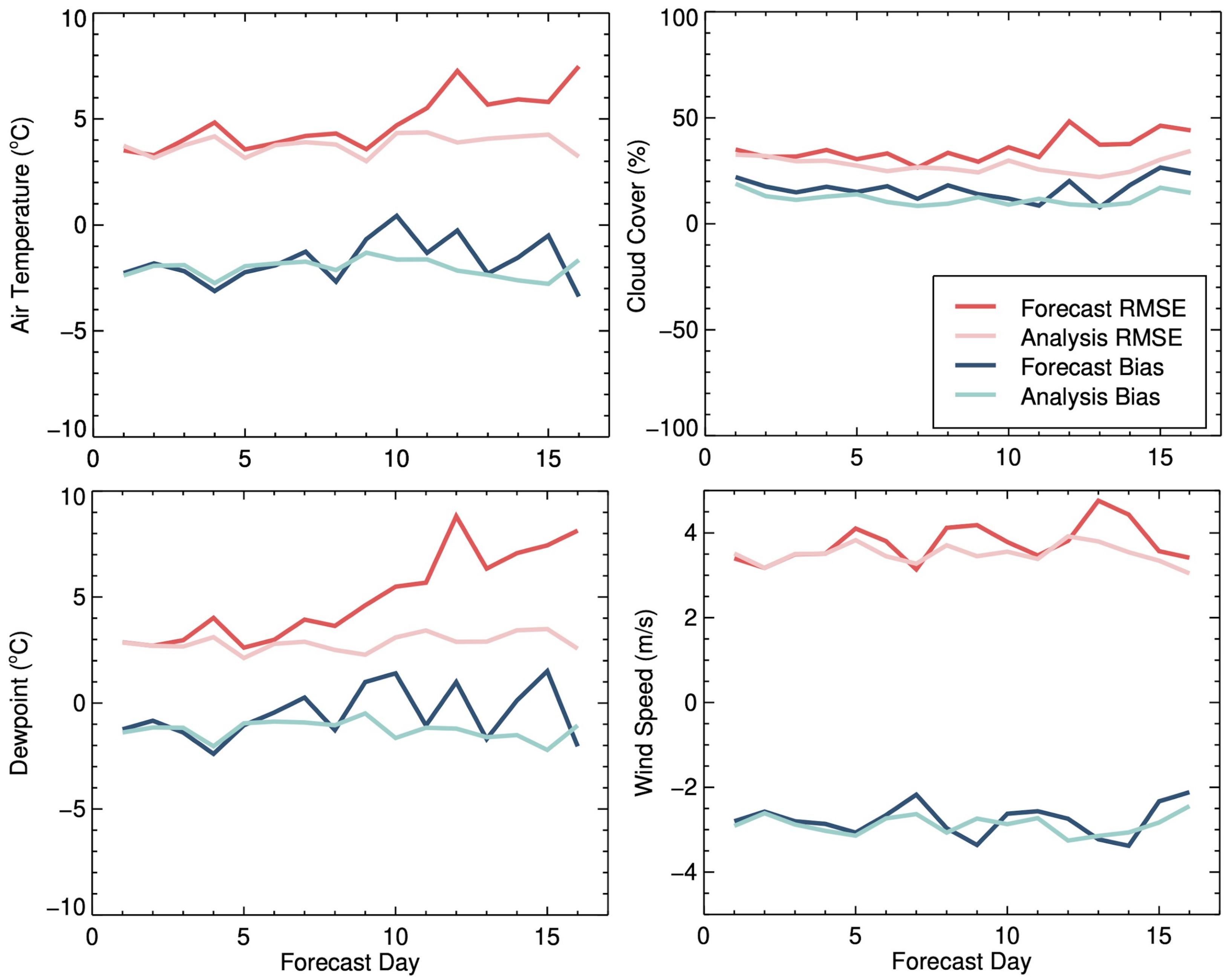


Test the GFS forecast and GFS analysis skill in comparisons to observations along the lake shores

RMSE and biases are averaged over all lake shores (161 stations) and all 8 16-day time periods for Jan-Apr 2022



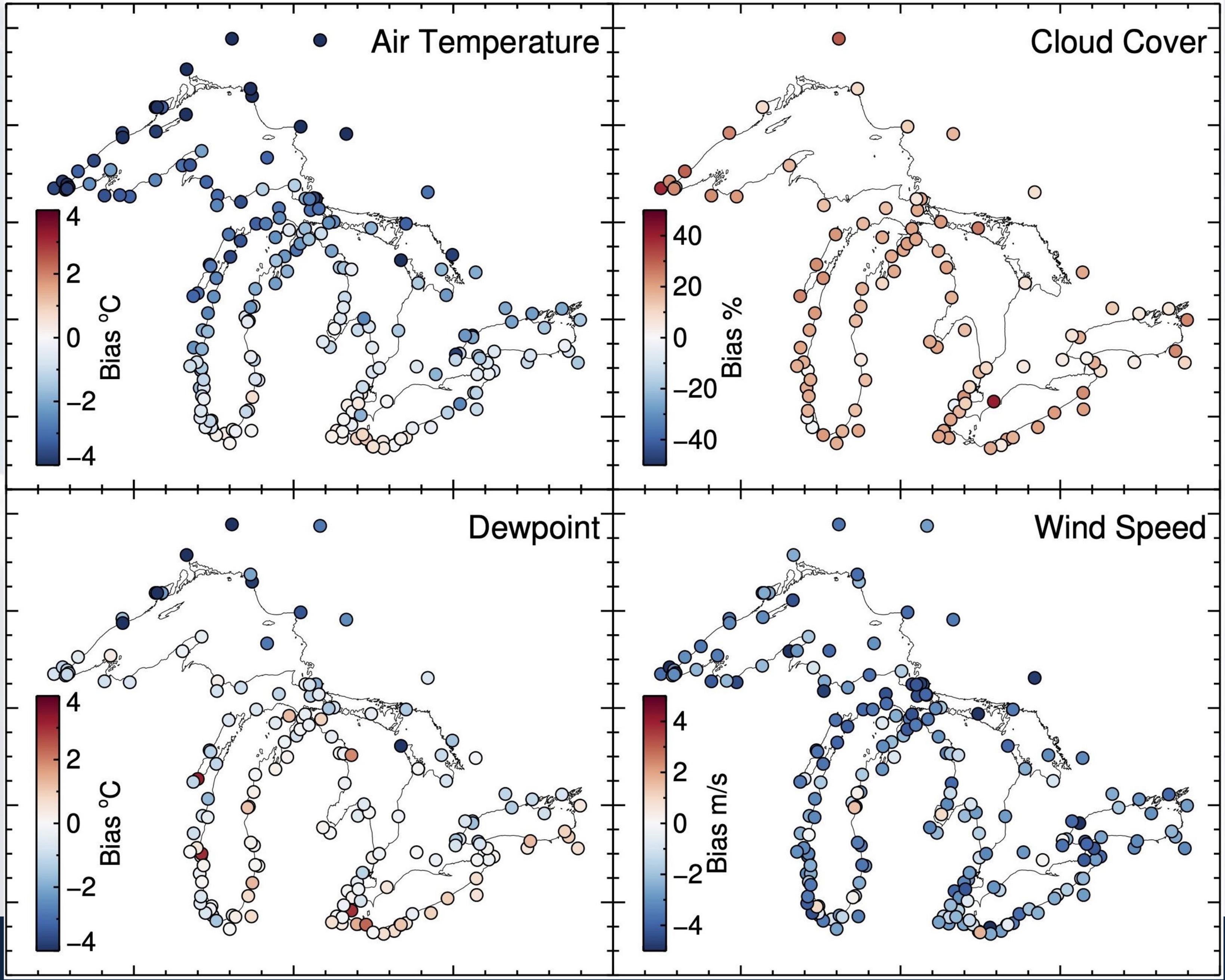
Stations, n=161



Assess the GFS forecast biases in comparisons to observations along the lake shores

GFS forecast skill in a nutshell:

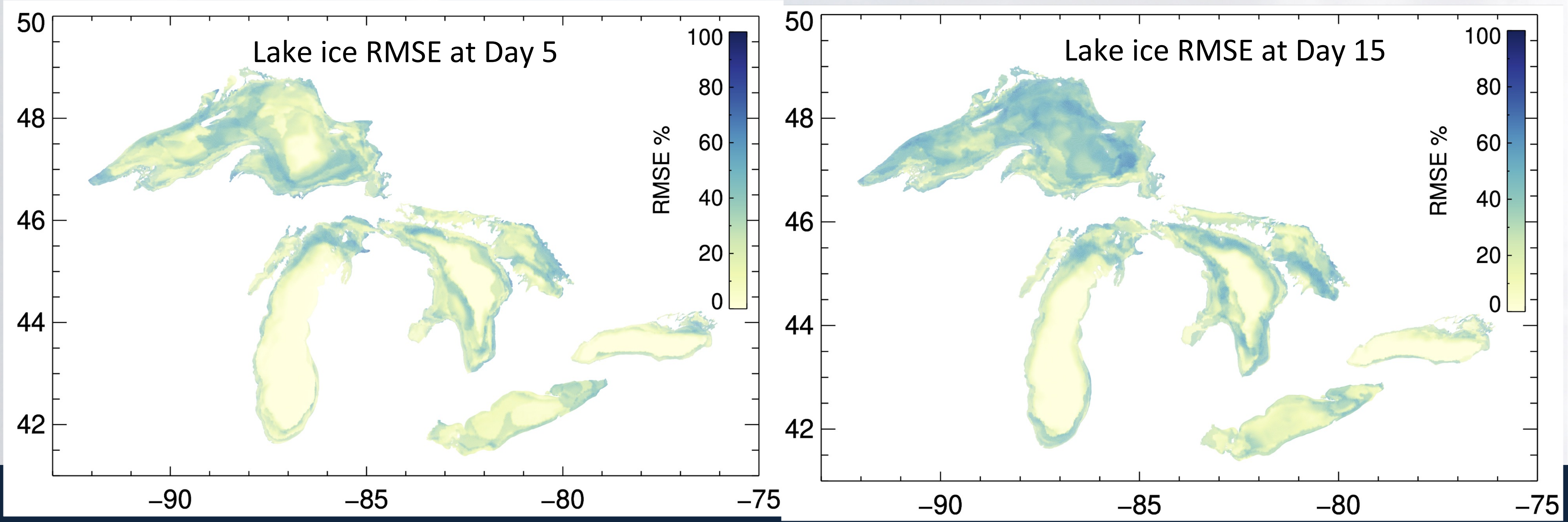
- Too cold with a north-south gradient
- Too cloudy
- Too calm



Mean GFS bias over forecast horizon (0-16 days) January – April 2022

Assess the FVCOM Ice RMSE in Comparisons to Observations

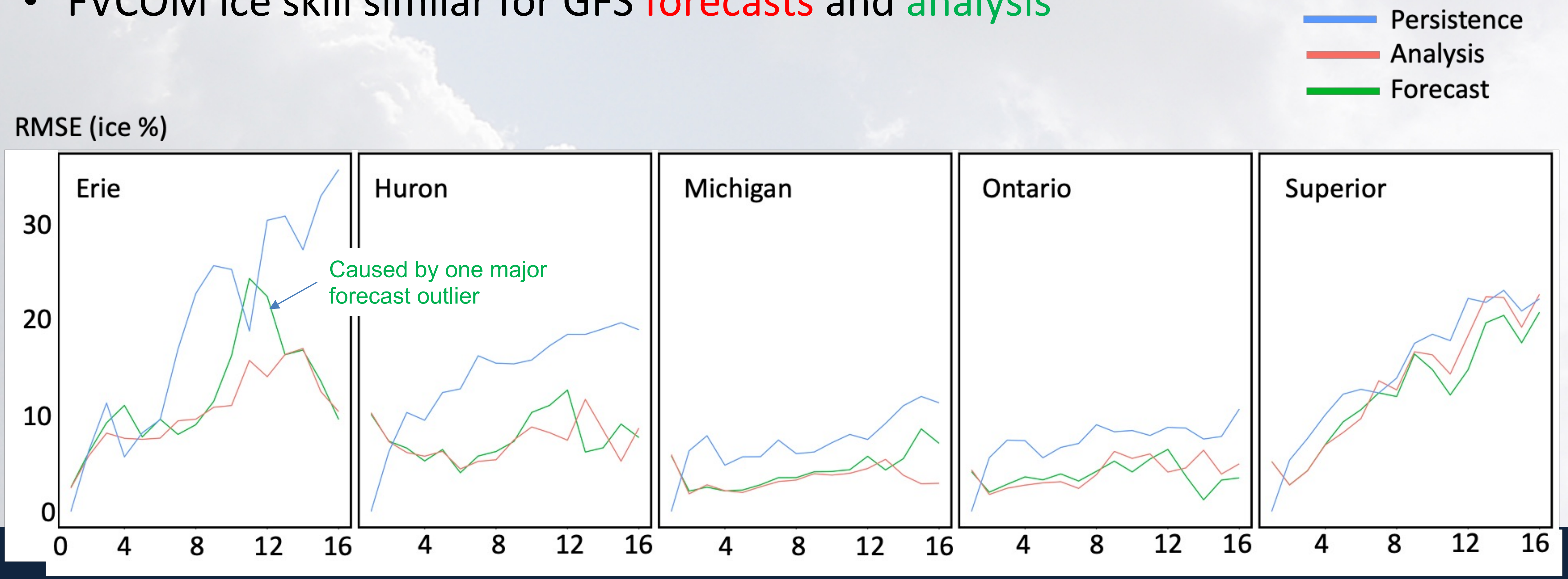
- GFS forecasts drive FVCOM over the 8 16-day forecast periods (Jan-Apr. 2022)
- Cold GFS biases (especially over Lake Superior) lead to increasing ice errors
- GFS-driven ice forecasts beat persistence! See next slide.



Mean FVCOM ice RMSE over forecast horizon (0-16 days) January – April 2022: day 5 and day 15 are shown

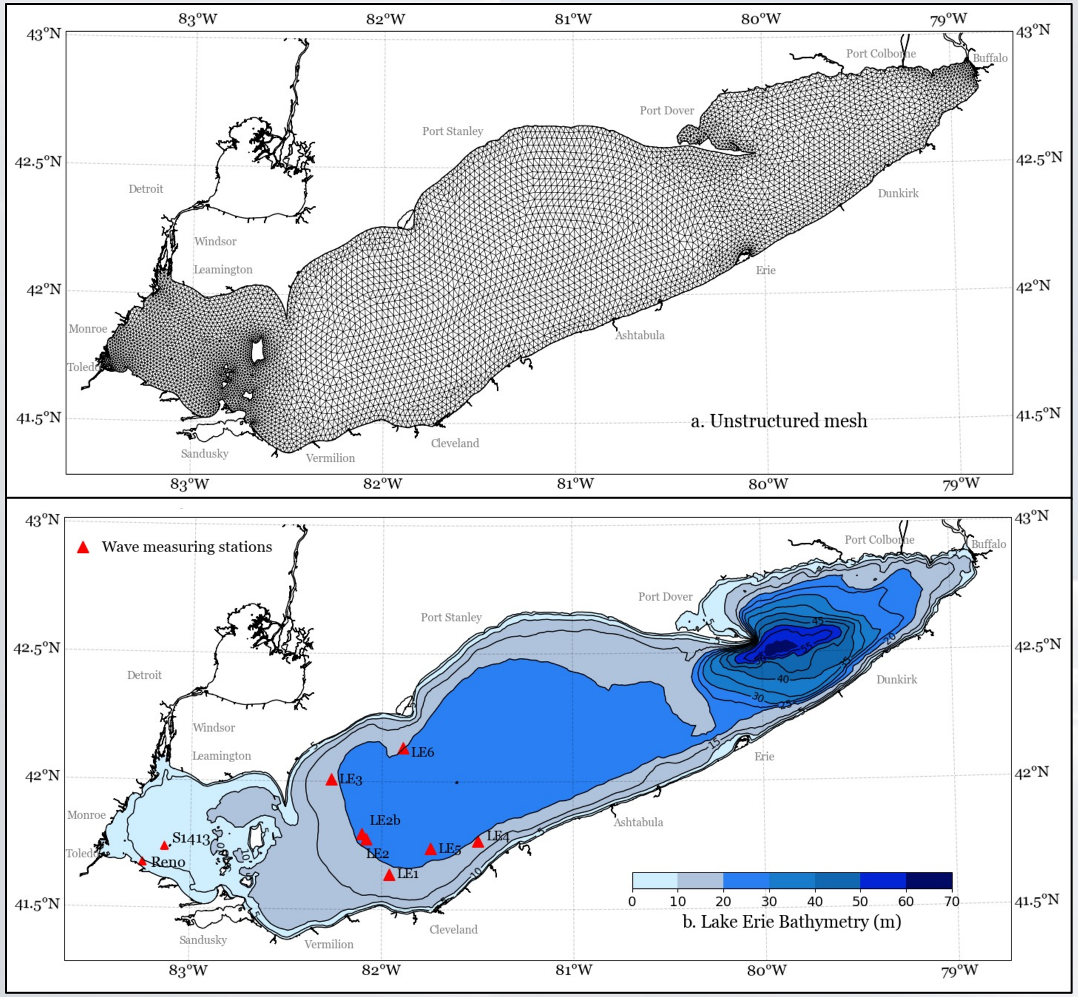
Assess the FVCOM Ice RMSE in Comparisons to Observations

- GFS-forecast-driven and GFS-analysis-driven FVCOM ice forecasts (GFS updates every 3hr/6hr) beat persistence (never updated)!
- FVCOM ice skill similar for GFS forecasts and analysis



Forecast day along the x-axis

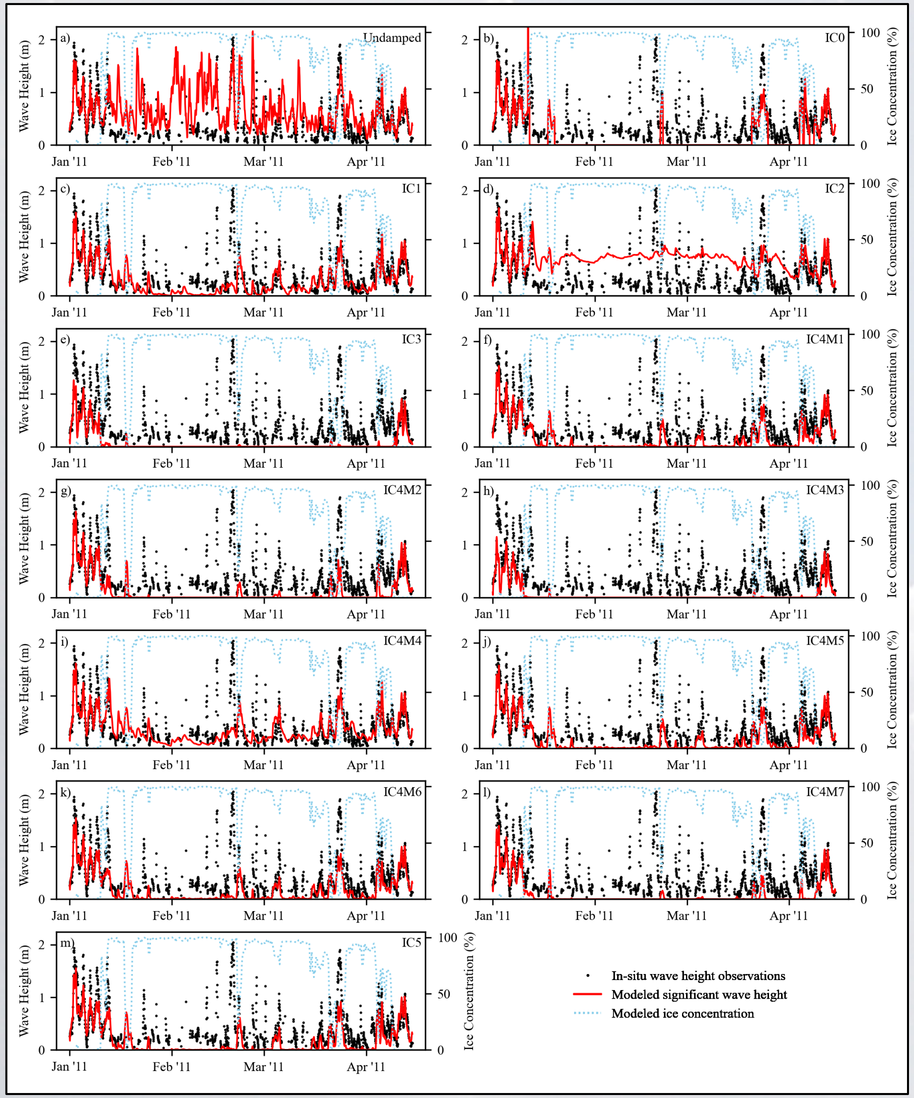
FVCOM-CICE - WW3 Wave Coupling

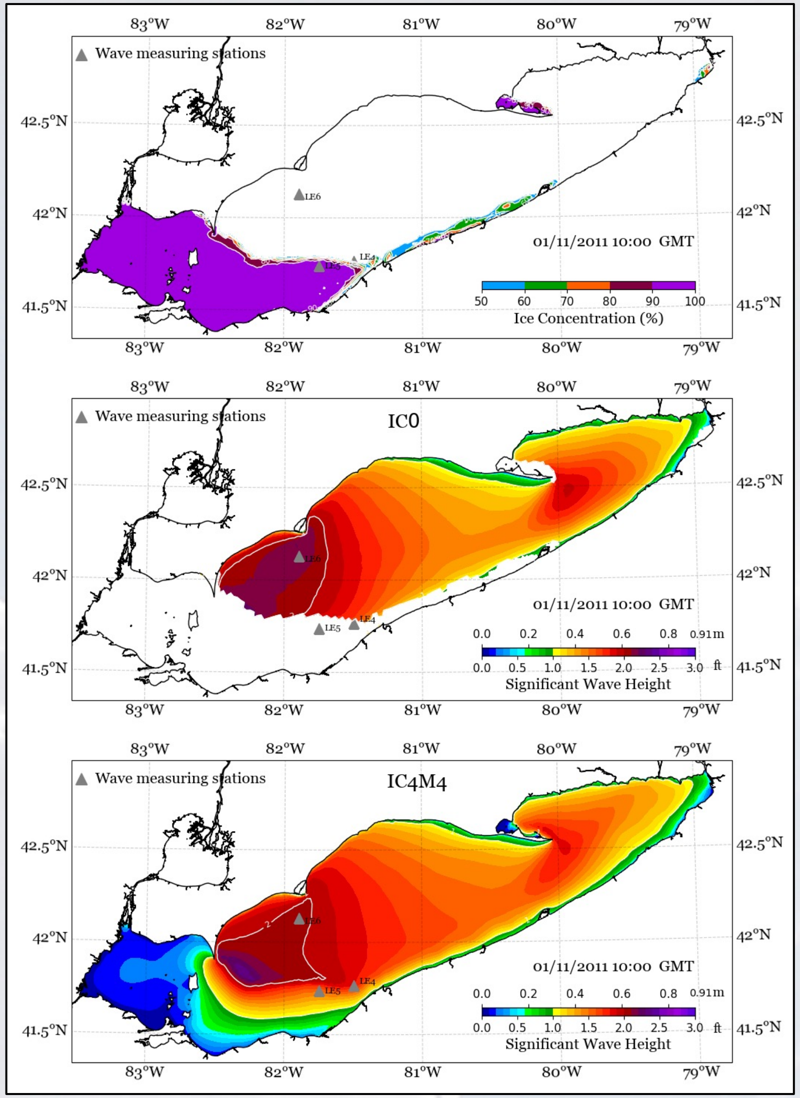


Scheme	Description
IC0	Simple ice blocking
IC1	Simple ice damping
IC2	Viscoelastic damping with ice modeled as continuous thin elastic plate
IC3	Viscoelastic damping with ice modeled as frazil ice floes
IC4M1	Empirical exponential damping as a function of wave period, with higher damping for smaller-period waves
IC4M2	Empirical polynomial-fit damping as a function of wave period, designed to be flexible
IC4M3	Empirical quadratic decay as a function of wave period and ice thickness, with higher attenuation for thicker ice and smaller-period waves
IC4M4	Empirical damping as a step function of significant wave height (Hs), with linear damping for Hs ≤ 3m and capped damping for Hs > 3m
IC4M5	Empirical damping as a step function of wave period, with four user-defined steps and damping coefficients
IC4M6	Empirical damping as a step function of wave period, with up to ten user-defined steps and damping coefficients
IC4M7	Empirical damping as a function of wave period and ice thickness
IC5	Viscoelastic damping with ice modeled as thin elastic plate restricted to one dimension

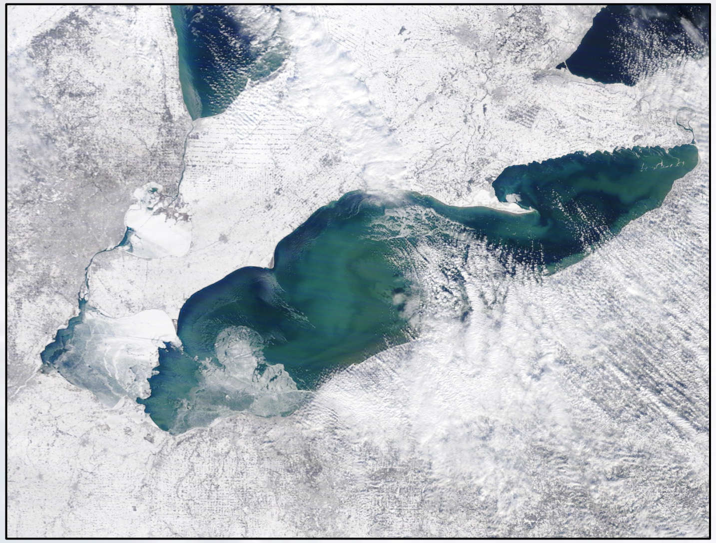
- FVCOM-CICE > WW3 one-way coupling tested to improve ice-wave physics
    - Ice cover dynamically simulated using FVCOM-CICE, and used as forcing to WW3
- 12 different ice-wave damping schemes available in WW3 were tested
- Simulations run for winters of 2010-11 and 2012-23, when in-situ under ice wave observations are available for validation

FVCOM-CICE - WW3 Wave Coupling





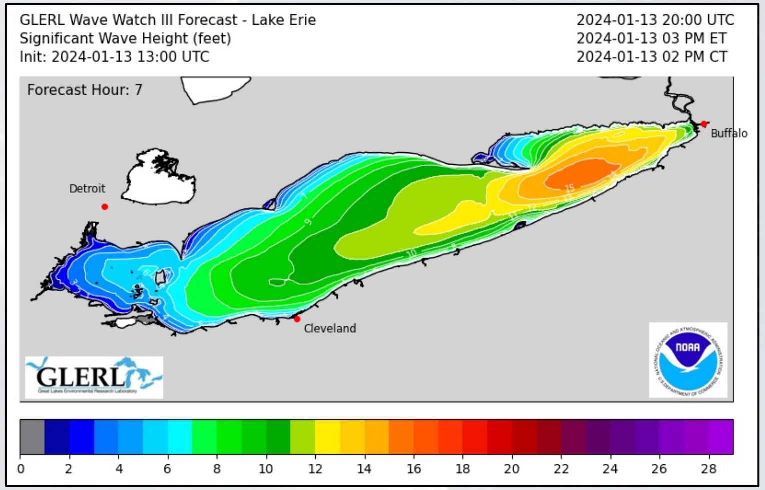
Simulated waves 11 January 2011 using IC0 vs IC4M4

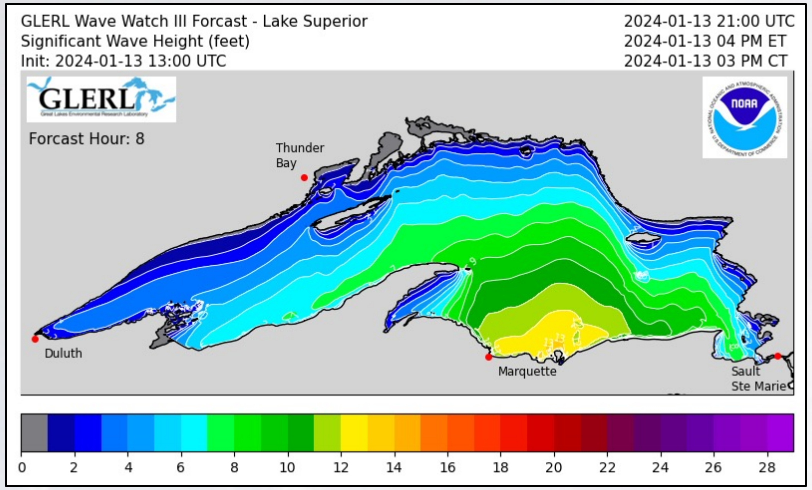


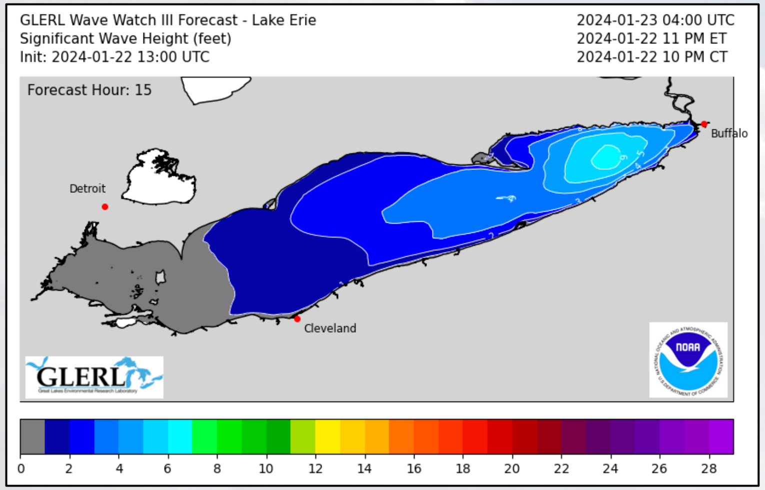
Moderate Resolution Imaging Spectroradiometer (MODIS) true color satellite image, taken 9 January 2011 (source: NOAA Coastwatch)

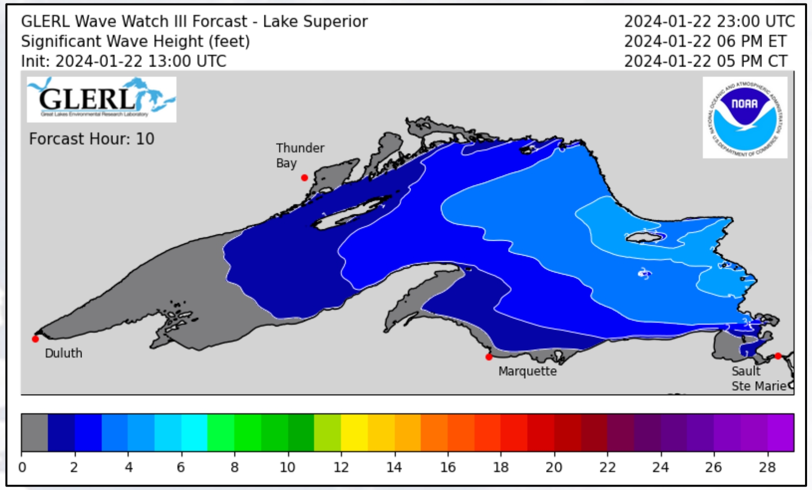
- The current operational system uses IC0 simple ice blocking which masks waves in areas over 50% ice and treats as land
- Of the methods tested, empirical IC4M4 method developed for marginal ice zone in Antarctic had the best skill
- Instead of total masking of waves for large portions of the lake, waves damp out gradually under the ice edge
    - Provides better forecast guidance and is more consistent with the fractional ice regime of Lake Erie

FVCOM-CICE - WW3 Wave Coupling: Towards Operational Wave Heights





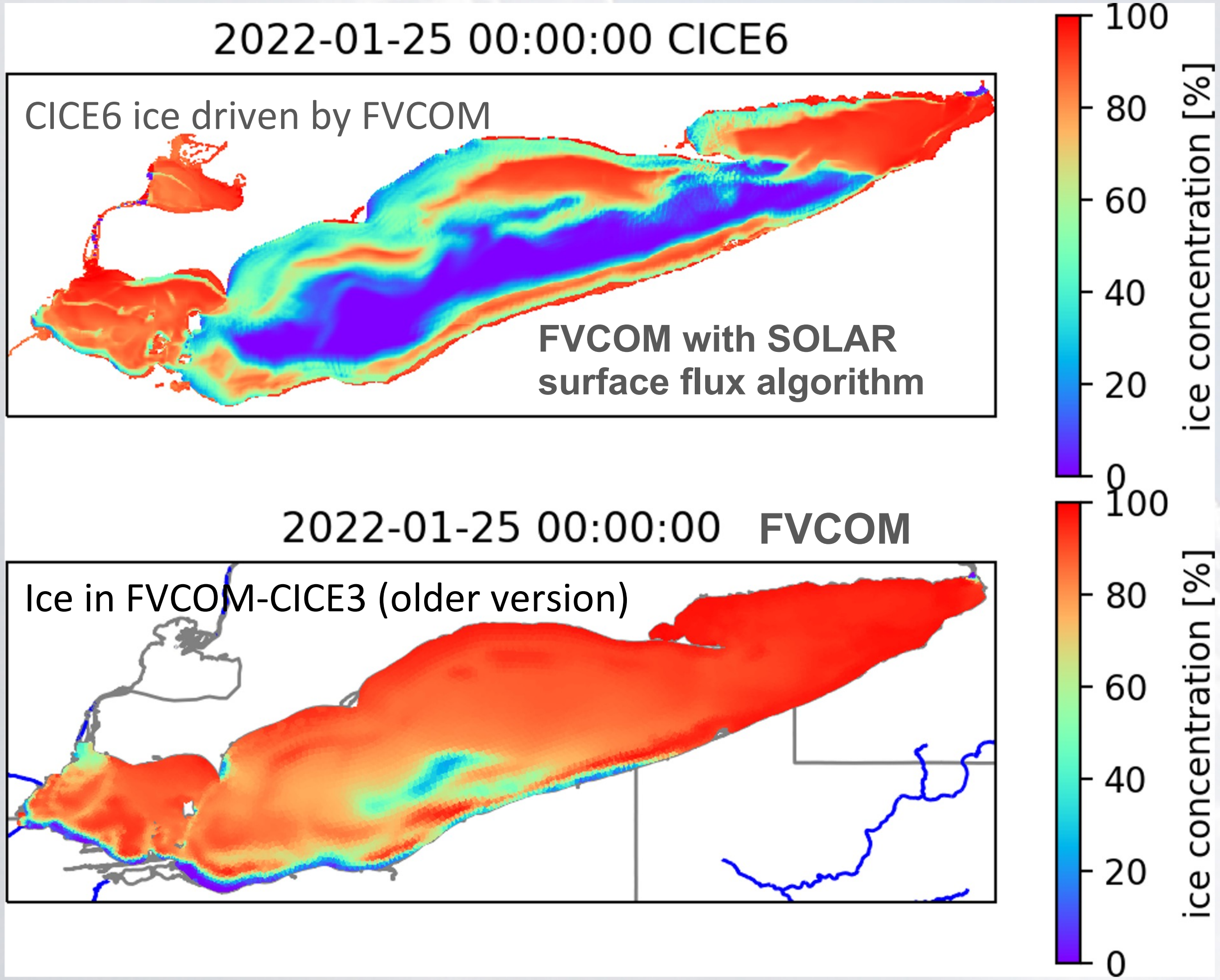


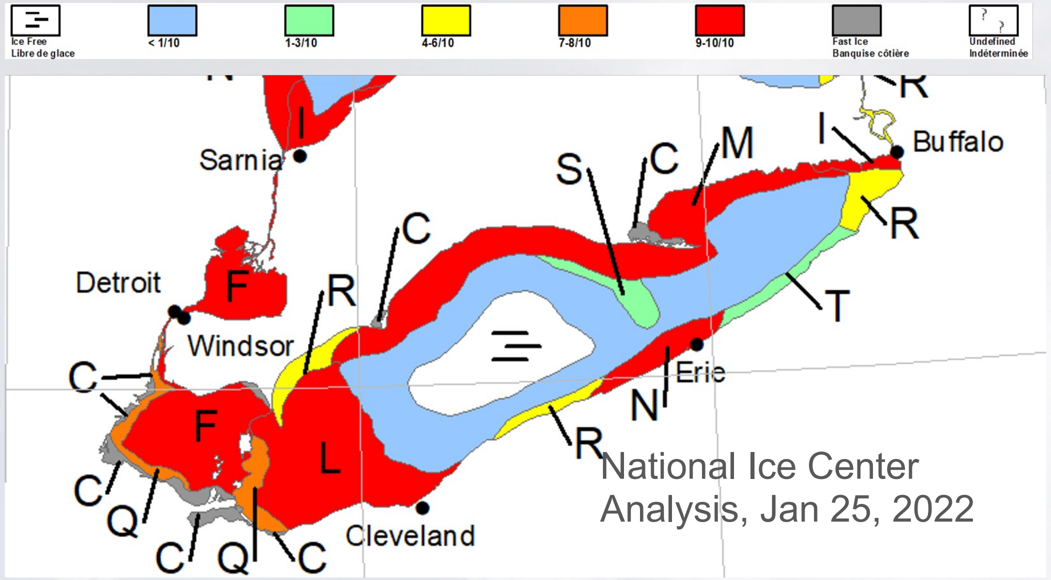


- Currently setting up experimental pseudo-operational model using improved IC4M4 ice-wave damping physics, with webpage for real-time testing and validation
- Plan to expand beyond Lake Erie and Lake Superior, to other Great Lakes
- Plan to develop UFS-based fully coupled test case to improve upon one-way coupling

Testing CICE6 standalone for Lake Erie: FVCOM has CICE3

Assess the Lake Erie ice coverage for a selected case study (Jan/25/2022)





Next steps include

- Test coupling CICE6 with FVCOM using UFS-Coastal Infrastructure
- Testing CICE6 in the other lakes

- CICE6 with 500 m grid spacing, driven by FVCOM hydrodynamics and HRRR atmospheric forcing
- CICE-6 & FVCOM-CICE comparison: noticeable differences. CICE6 appears to better capture discrete feature of ice field (lead opening etc)

Summary: Lots of Developments are Under Way

- Coupling of the dynamic FVCOM lake conditions using the newest UFS ESMF-based coupling infrastructure: inlining the CDEPS data model, tested for UFS-SRW/RRFS
- ESMF enables the seamless inclusion of dynamic FVCOM lake conditions in both UFS-SRW/RRFS and the Medium-Range Weather (UFS-MRW) application
  - test the skill of a coupled UFS-MRW/GFS-FVCOM configuration
  - Test the UFS-MRW/GFS-FVCOM with the ESMF CDEPS infrastructure
- 1-way coupling of FVCOM to the wave model WaveWatch III (WW3):
  - Lake Erie and Superior tests under way, other lake to come
  - Can/should WW3 supply the momentum forcing for the UFS?
- Upgrades & evaluation of the ice representation in FVCOME: CICE3 versus CICE6
  - Towards a potential upgrade to CICE6 in FVCOM (using ESMF?)

Questions?